UNIVERSITI PUTRA MALAYSIA

GLOBAL SEARCH OPTIMIZATION ALGORITHM FOR VEHICLE ACTIVE SUSPENSION

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GLOBAL SEARCH OPTIMIZATION ALGORITHM FOR VEHICLE ACTIVE SUSPENSION

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

Dedicated to my family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

GLOBAL SEARCH OPTIMIZATION ALGORITHM FOR VEHICLE ACTIVE SUSPENSION

By

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December 2017

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Automotive suspension system provides comfort by isolation ground vibration from passenger. An active system consists of vehicle mass, spring, damper and actuator. The response of vehicle is measured by the amplitude and frequency of its vertical displacement. The response depends on the parameters such as vehicle mass, spring stiffness, damping coefficient, force and time. The equation of motion relating the response with the parameters is complex. The solution can be obtained either by analytical, numerical and/or experimental methods. The analytical method is limited to simple cases, whereas experimental method is costly. Hence, numerical method, namely, the Direct Transcription (DT) and Global Search (GS) can be used. In the present work the GS method is used. The results are compared with analytical, DT and experimental.

The objective of global optimization is to find the globally best solution of (possibly nonlinear) models, in the (possible or known) presence of multiple local optima. Formally, global optimization seeks global solution of a constrained optimization model. Nonlinear models are ubiquitous in many applications, e.g., in advanced engineering design, co-design problems, biotechnology, data analysis, environmental management, financial planning, process control, risk management, scientific modeling, and others. Their solution often requires a global search approach.

Spring stiffness and damping coefficient were determined using GS optimization approach with a control input force was applied directly to the active suspension system.

A design methodology for optimizing the passive suspension parameters was developed and illustrated on 1/4 car model. The dynamics of the suspension system were analyzed as the control force value is increased gradually. The optimization numerical results were simulated in time and frequency domains.

A very important results of the research was that there are fundamental trade-offs between ride quality and road holding that are independent of suspension type or design due to the value of the damping ratio.

GS Simulations in time and frequency domains were conducted comparing the optimized passive and active suspensions under the same performance index and single bump sinusoidal road profile. It was shown that the active suspension can provide significant performance improvements over the passive suspension and comparable to the active suspension obtained by DT in terms of spring stiffness and damping coefficient.

An experimental test rig was to validate the optimal numerical results and the dynamic responses in frequency domain.

The analytical simulations were investigated. It was found that the optimal active suspension system in the absence of the control force showed less sprung mass acceleration overshoot and settling time, compared to optimal passive suspension system and DT model. In the frequency domain, the frequency response in terms of natural frequency obtained for GS is 1.26 Hz, DT is 1.35 Hz and experimental is 1.32 Hz. The percentage error between experiment and GS is 4.18% and between experiment and DT is 2.6%. For magnitude, GS gave 5.63 dB, DT gave 8.56 and experiment is 13.12 dB. The difference between GS and experiment is 57.1% and DT and experiment is 0.348%.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ALGORITMA PENGOPTIMUMAN CARIAN GLOBAL UNTUK GANTUNGAN AKTIF KENDERAAN

Oleh

MUNA KHALIL SHEHAN

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Sistem gantungan automotif memberikan keselesaan melalui pemencilan getaran jalan dari penumpang. Sebuah sistem aktif terdiri daripada berat kenderaan, pegas, peredam dan penggerak. Tindakbalas kenderaan diukur secara amplitud dan kekerapan anjakan menegak . Tindakbalas bergantung kepada pembolehubah seperti berat kenderaan, kekakuan pegas, pekali redaman, daya dan masa. Persamaan gerakan yang mengaitkan tindakbalas dengan pembolehubah adalahrumit. Penyelesaiannya boleh dibuat sama ada melalui kaedah analisis, berangkadan / atau ujikaji. Kaedah analisis adalah terhad kepada kes mudah, sedangkan kaedah ujikaji adalah mahal. Oleh itu, kaedah berangka, iaitu Transkripsi Langsung (DT) dan Carian Global (GS) boleh digunakan. Dalam kerja ini, kaedah GS digunakan. Hasilnya dibandingkan dengan analisis, DT dan ujikaji.

Objektif pengoptimuman global ialah untuk mencari model penyelesaian terbaik, dengan kehadiran pelbagai keadaan optimum setempat. Model tak linar banyak penggunaannya seperti dalam reka bentu kejuruteraan automotif termaju, analisis data, kawalan proses dan permodelan saintifik. Penyelesaian masalah tersebut memerlukan kaedah carian global.

Kekakuan pegas dan pekali redaman telah ditentukan dengan menggunakan pendekatan pengoptimuman GS dengan satu kawalan daya masukan dikenakan secara langsung keatas sistem gantungan aktif.

Kaedah rekabentuk untuk mengoptimumkan parameter gantungan pasif telah dibangunkan dan ditunjukkan pada model 1/4 kereta. Dinamik sistem gantungan telah dianalisis dengan menaikkan nilai daya kawalan secara beransur-ansur. Hasil pengoptimuman berangka telah disimulasikan dalam domain masa kekerapan.

Dapatan yang sangat penting dari penyelidikan ini ialah terdapat pertukaran asas antara kualiti perjalanan dan penetap jalan yang bebas daripada jenis atau reka bentuk gantungan kerana nisbah nilai redaman.

Simulasi GS dalam domain masa dan kekerapan telah dijalankan dengan membandingkan gantungan pasif dan aktif yang telah dioptimumkan di bawah indeks prestasi yang sama dan profil jalan sinusoidal yang tunggal. Didapati bahawa gantungan aktif dapat memberikan peningkatan prestasi yang bererti melebihi gantungan pasif dan dibandingkan dengan gantungan aktif yang diperoleh secara DT dari segi kekakuan pegas dan pekali redaman.

Sebuah rig ujikaji telah digunakan untuk pengesahan keputusan dari pengoptimuman berangka dan tindakbalas dinamik dalam domain kekerapan.

Analisis simulasi telah dijalankan. Didapati bahawa pengoptimuman sistem gantungan aktif dengan ketiadaan daya kawalan menunjukkan pengurangan pecutan lajak jisim terpegas dan masa pengenapan, berbanding dengan pengoptimuman sistem gantungan pasif dan model DT. Dalam domain kekerapan, tindak balas kekerapan dari segi kekerapan tabii yang diperolehi secara GS adalah 1.26 Hz, DT adalah 1.35 Hz dan ujikaji adalah 1.32 Hz. Peratusan ralat antara ujikaji dan GS adalah 4.18% dan antara ujikaji dan DT adalah 2.6%. Untuk magnitud, GS memberikan 5.63 dB, DT memberikan 8.56 dan ujikaji adalah 13.12 dB. Perbezaan antara GS dan ujikaji adalah 57.1% dan; DT dan eksperimen adalah 34.8%.

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This thesis was submitted to Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND NOTATIONS

2DOF	Two degree of freedom
RMS	Root mean square
FSD	Frequency selective damping
HIL	Hardware-in-the-Loop
PID	Proportional–integral–derivative
ER	Electro-rheological
MR	Magneto-rheological
ECASS	Electronically controlled suspension system
ADD	Acceleration driven damper
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
LPV	Linear parameter varying
ECASS	Electronic consolidated automated support system
MPC	Model predictive control
SMC	Sliding mode control
ISO	International organization for standardization
NVH	Noise, vibration and harshness
SISO	Single input single output
OCSD	Optimal control-system design
HJB	Hamilton-Jacobin-Bellman
PMP	Pontryagin's maximum principle
KKT	Karush-Kuhn-Tucker
NLP	Non-linear programming
DAE	Differential algebraic equation

MDF	Multidisciplinary Feasible
DT	Direct Transcription
AAO	All-at-One
ODSD	Optimal dynamic system design
u	Ground displacement
k_t	Tire stiffness
c_t	Tire damping coefficient
m_u	Unsprung mass
x_u	Unsprung mass displacement
k_s	Suspension spring stiffness
c_s	Suspension damping coefficient
m_s	Sprung mass
x_s	Sprung mass displacement
$\ddot{x}_u$	Unsprung mass acceleration
$\ddot{x}_s$	Sprung mass acceleration
f	Control force
u	Ground displacement
k_t	Tire stiffness
c_t	Tire damping coefficient
m_u	Unsprung mass
x_u	Unsprung mass displacement
k_s	Suspension spring stiffness
η	Plastic viscosity
τ_o	Yield strength
k_P	Seat suspension stiffness

m_p	Seat mass
c_p	Seat damping coefficient
x_p	Passenger seat displacement
Ξ	State matrix
ζ	Damping ratio
ω_n	Natural frequency
x	State variable
$\dot{x}$	State variable derivative
$\ddot{x}_s$	Sprung mass acceleration
x_o	Initial value
v	Vehicle velocity
x_r	Road elevation
ρ	Optimization parameter
$j\omega$	Imaginary number
ω_d	Damped natural frequency
H	Hamiltonian derived
p_0	The abnormal multiplier non-positive scalar
N_a	Spring Pitch
ss	State space model
lsim	Linear Simulation function
lsiminfo	Linear simulation information function
d	Spring wire diameter
D	Spring helix diameter
G	Shear modulus
i	Current

V	Voltage
dB	Decibel
Hz	Hertz
F	Control force

CHAPTER 1

INTRODUCTION

1.1 Introduction

Automotive suspension systems are designed to provide ride comfort and handling. It is also designed to isolate the vibration from the road to passenger. The road usually is not smooth. For passenger comfort, ideally, the vehicle should not oscillate vertically. However, in reality, the amplitude of vibration acceleration and frequency needs to be limited to the value tolerate to humans. The basic system consists of mass of vehicle, spring and damper. The response of vehicle travelling in forward direction is usually measured by the frequency and amplitude of its vertical displacement. The response depends on the values of vehicle mass, spring stiffness and damping coefficient. The values are determined such critical damping occurs and no resonance. For fixed values, the system is said to be passive. Passive system has many disadvantages because it can solely of energy of storage and dissipation elements (spring and damper). However; these passive elements can transmit forces that depend on relative vehicle chassis/tire motion, without the ability to introduce external energy that can generate forces which depend on absolute vehicle chassis motion.

To overcome the drawback of passive suspension systems, automotive active suspensions have attracted aroused a great deal of interest due to their potential to improve the traditional ride quality and handling trade-off. The automotive industry has begun to seriously consider modulated, semi active and full active suspensions, and have produced promising prototype systems. In general these systems have been developed by "cut and try" methods using prototype vehicles as test beds (Butsuen, 1989). This approach usually leads to sub-optimal performance and is also very expensive. The resulting design is often very sensitive to environmental changes and vehicle aging. It also has the disadvantage that because of the development procedure, only a few people are familiar with the control software resulting in great difficulty if the system changes are required. A design methodology is needed that would allow much of the design to be done by computer aided design methods and only the final "tuning" and verification achieved by prototype testing.

1.2 Problem statement and motivation

Car suspension provides ride comfort by isolating the passengers from road disturbances and improves handling by controlling the contact forces between the car chassis, tire and the road. These demands are mutually conflicting Figure 1.1. Softer suspension offer more comfort at the cost of degraded handling. Suspension system design trades these demands off by a weighted performance index function for optimization. However; active suspension system has two major drawbacks:

1) The actuators in active suspension require large power.
2) The malfunction of the controllers may cause total system breakdown (hard failure) or slow degradation of the vehicle.

The motivation behind this goal is associated with the conflicting between the ride comfort and road holding (Eamcharoenying, 2015). The suitability and viability of suspension systems are highly dependent on the spring stiffness and damping coefficient, the ride comfort and the road holding requirements (Fathy, 2003).

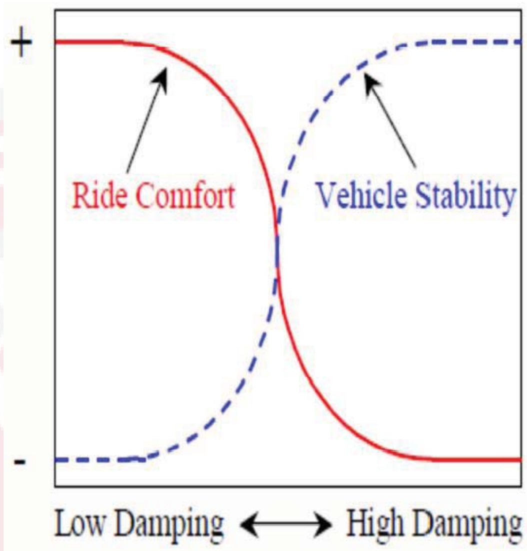

Figure 1.1 : Suspension Compromise
(Aly et al. 2013)

In the present work, global optimization technique for combined the passive and active suspension elements based on Global Search approach was implemented. The proposed method is gradient free algorithms that can overcome the nature of the objective function drawbacks like non-smoothness (Allison, 2014). In this study the used objective function is a single system that combined the three conflicting objectives (ride comfort, handling, and control force). Simulation algorithms in time domain and frequency domain were developed to predict the dynamic response performance of the suspension system for a sinusoidal motion to validate the numerical optimization algorithm results as shown in Figure 1.2. We use the speed bump profile shown in Figure 1.2 as the input to the quarter car model.

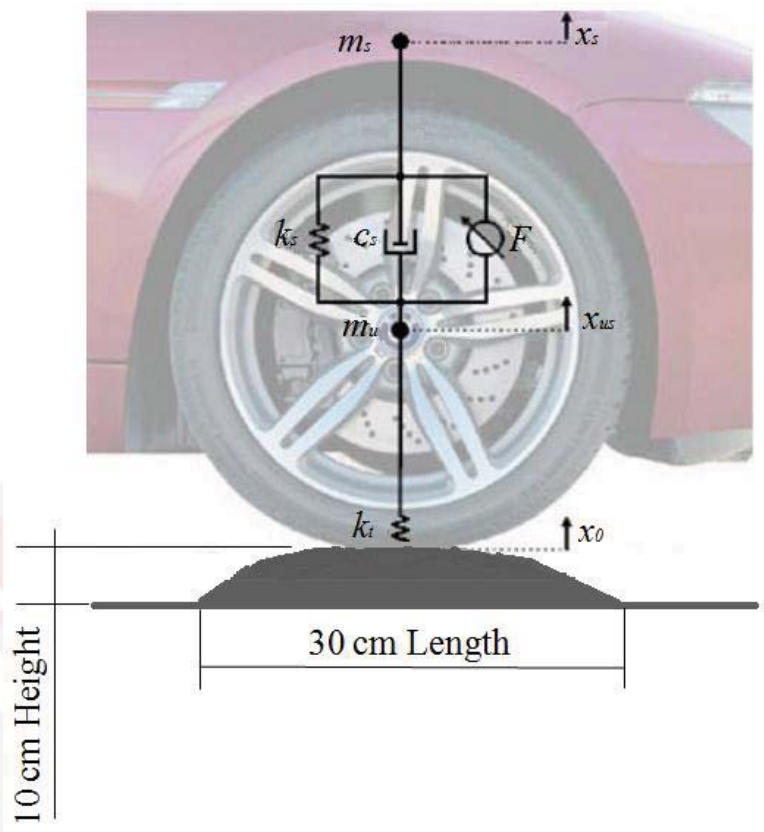

Figure 1.2 : One quarter car model
(Hyniova, 2013)

1.3 Aim and objectives of study

This research aims to design a methodology for optimizing the passive suspension parameters; namely, mass, spring stiffness, damping coefficient and control force, and illustrated on a quarter car model active suspension system subject to:

1) Dynamic constraints.
2) Boundary constraints.
3) Control force constraints.

To achieve the study aim, the following objectives are as follows:

1) To develop design framework for quarter car model based on Global Search method to find the numerical values for optimum spring stiffness and damper coefficient. The design of optimum suspension trades the ride comfort and road holding off by grouping them into a weighted performance function for optimization.

2) To determine the effect of control force on the suspension system dynamic behavior by assuming open loop control because the control input is specified directly and varied level of control authority.
3) To determine the dynamic properties response in time and frequency domains for quarter car model that is to be driven over a speed bump at a forward velocity of v.
4) To validate the quarter car optimal design algorithm for optimal spring stiffness and damping coefficient and dynamic response of sprung mass.

1.4 Scope of study

Design, simulation and modeling optimal suspension system are a demand in this research to investigate the dynamic response of the proposed system. GS method was suggested to come up with optimal spring stiffness and damping coefficient because it is a powerful method for searching complicated objective function spaces such as Lagrange term to quantify handling and comfort characteristics of the vehicle suspension system where the objective function provides increasingly detailed insights into system behaviors.

To achieving the research demand, the research objectives were set. The first objective is proposed design framework. This framework combines the optimization algorithm outcome of the Global Search technique and the simulation techniques to integrate the optimal numerical values in terms of spring stiffness and damping coefficient and investigate the dynamic response of the proposed model in terms of sprung mass acceleration and suspension natural frequency. The phase stages of design technique were done by utilizing MATLAB numerical engine as a tool because it provides the needed tools in the field of optimization techniques. Results were obtained from the implementation of the design framework and evaluated by comparing the obtained results with original studies. A test rig for quarter car suspension system was designed to validate the optimization and simulation results.

However; there is some limitation by assuming suspension system dynamic behavior is linear. Quarter car active suspension was studied on the subject have dealt with car model possessing linear characteristics (i.e. the damping force is proportional to the velocity of the mass and acts in the direction opposite to the motion, the springs are long enough to remain almost straight when the suspension oscillates) and mechanical model subjected to deterministic road excitation.

1.5 Thesis organization

The thesis is divided into five chapters. Chapter one is the introduction followed by Chapter Two literature review discusses different types of suspension system with its components, and different techniques of optimal design that commonly utilized in the context of optimal active suspension system.

Chapter Three present a description of the methodological framework followed by Chapter Four where the results and discussion are presented.

This is followed by Chapter Five which summarized the conclusion and finally ends with Chapter Six on recommendation for further work.

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