INVESTIGATION OF ADJUSTABLE VALVE OF SEMI-ACTIVE DAMPER FOR IMPROVING RIDE COMFORT IN A PASSENGER CAR

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Elemen penting dalam sesebuah kenderaan ialah sistem suspensi atau lebih dikenali sebagai suspensi. Fungsi utama sistem suspensi adalah untuk mengawal struktur kenderaan ketika berlakunya sebarang gegu atau getaran disebabkan oleh struktur permukaan jalan yang tidak rata. Terdapat dua objektif utama yang ingin dicapai iaitu untuk mendapatkan perjalanan yang selesa serta mengendalikan kenderaan dengan baik. Pemanduaan yang selesa lazimnya berkadar songsang dengan kadar pecutan sesebuah kenderaan manakala pengendalian kenderaan pula berkait diantara kerangka sesebuah kenderaan dan tayar yang digunakan. Tesis ini adalah cuba untuk merealisasikan daya redaman di dalam tiub berkembar dan tiub tunggal memgunakan model matematik. Model-model ini menunjukkan corak yang sama, manakala kekuatan yang berlainan direkodkan, kerana tekanan dalam ruang pemampatan meningkat semasa pemulihan dalam peredam tiub berkembar dan dalam peredam tiub tunggal kebuk gas sentiasa bersambung ke kebuk mampatan. Ujian kejutan dyno dilaksanakan untuk menentusahkan model tiub berkembar melalui data percubaan. Satu bentuk prototaip berkeupayaan untuk menyerap separu aktif kejutan melalui laras elektronik dari tiub berkembar dibangunkan, ini dicapai dengan melampirkan motor stepper bagi setiap penyerap kejutan yang membantu dalam menyesuaikan orifis berdarah ke posisi tertentu yang menggantikan aliran minyak hidraulik dalam penyerap kejutan antara ruang omboh semasa proses pemampatan dan pengembanyan. Seterusnya dalam usaha untuk menilai kesan penyerapan kejutan separu aktif terhadap pergerakan kenderaan yang dinamik maka beberapa ujian telah dilaksanakan terhadap beberapa jenis jalan seperti jalan yang bergelombang, jalan yang lurus dan di kawasan-kawasan bulatan jalan. Ujian ini digunakan untuk menilai kadar pecutan dan kualiti sesebuah kenderaan ketika melakukan perjalanan. Hasil tindak balas dari ujian ini satu nilai julat besar diperolehi, orifis berdarah menunjukkan pencapaian 35% diantara kadar kaku dan lembut penyerapan kejutan ini.Nilai asal untuk pecutan persegi (RMS) dikira dan dibandingkan dengan nilai piawa tubuh badan manusia terhadap getaran dan didapati terdapat perbezaan sebanyak 6%. Hasiln ini menunjukkan bahawa kesan penyerapan kejutan terkawal secara elektronik terhadap pergerakan yang dinamik sesebuah kenderaan. Kelebihan penyerapan secara elektronik ialah mampu meningkatkan prestasi keselesaan sesebuah perjalanan dan mengurangkan ketidakselesaan akibat daripada getaran yang tidak diinginkan. Untuk menilai daya yang dihasilkan oleh model pelarut monotube separu aktif pada tingkah laku dinamik kenderaan, model dianalisis dan dibandingkan dengan strategi kawalan langit-pasif dan aktif pada kereta suku yang menggunakan dua jenis jalan (pengujaan rawak, bergelombang). Gerakan heteresis dengan set diameter orifis yang berbeza dihasilkan. Pendekatan reka bentuk pengawal PID telah diperiksa dengan CVD untuk menilai prestasi peredam separu aktif, di mana kombinasi menunjukkan pengurangan dalam kedua-dua pecutan badan dan anjakan menegak yang berbeza dengan pasif dan On / Off hook-hook 73.4% dan 53.8% masing-masing dan juga menjual masa sebanyak 79% dan 59% untuk jalan bergelora. Ini menganggap peningkatan ke arah keselesaan perjalanan dan kestabilan kenderaan.

ABSTRACT

The suspension of a car is considered as an essential element in the vehicle. The primary function of the suspension system is to isolate the vehicle structure from shocks and vibration due to the irregularities of the road surface. Two primary objectives need to be satisfied which are ride comfort and road handling. Ride comfort is inversely proportional to the absolute acceleration of the vehicle body, while the road handling is linked to the relative displacement between the vehicle body and the tires. The thesis attempted to realize the damping force in twin and monotube by developing a mathematical model. The models show similar trends, while different forces are recorded, due to the pressure in the compression chamber increases during rebound in twin tube damper and a monotube damper the gas chamber is always connected to the compression chamber. Shock dyno testing is carried out to validate the model of twin tube with experiment data. A prototype of electronically adjustable semi-active shock absorber from available twin tube is developed, this achieved by attaching stepper motor for each shock absorber which helps in adjusting the bleed orifice to a particular position that alternates the hydraulic oil flow in the shock absorber between piston's chamber during the process of compression and rebound. To evaluate the effect of the developed semi-active shock absorber on the dynamic behavior of the vehicle, several tests were carried out on different types of road condition (bumpy, straight-line and roundabout). These tests were used to evaluate the acceleration and ride quality. There is a great range in response when the bleed orifice is opened reached up to 35% between the stiff and soft setting. The value of root means square acceleration (RMS) was calculated and compared with the standard of human exposure to whole-body vibration, which shows an error of 6% slightly. The result shows the effect of the electronically controllable shock absorber on a vehicle's dynamic behavior. The advantage of electronics to improve the performance of ride comfort and reduced the harms due to undesired vibration. To evaluate force generated by the developed model of the semi-active monotube damper on the dynamic behaviour of the vehicle, the model was analyzed and compared with the passive and On/Off sky-hook control strategy in the quarter car using two different types of road (random excitation, bumpy) as input to the quarter car model. Force hysteresis loop with different sets of orifice diameter was generated. PID controller design approach has been examined with CVD to evaluate semi active damper performance, where the combination shows a reduction in both body acceleration and vertical displacement contrasting with passive and On/Off sky-hook 73.4% and 53.8% respectively and also the selling time by 79% and 59% for a bumpy road. This considered an improvement toward the ride comfort and vehicle stability.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a	Acceleration, m/s^2
a_{fw}	Frequency-weighted acceleration, m/s^2
A_b	Area of the bleed valve, m/s^2
A_{gp}	The cross-section area of the floating piston, m/s^2
A_{pt}	Area of the piston, m^2
A_{fv}	Flow space through the base valve, m^2
A_{rod}	Area of the piston rod, m^2
A_v	Flow area through the piston valve, m^2
C_{max}	Maximum damping coefficient
C_{min}	Minimum damping coefficient
C_s	Damper coefficient
C_{sa}	Semi-active damping coefficient
C_{sky}	Skyhook damping coefficient
C_d	Discharge coefficient
D_p	The diameter of the piston, m
D_v	The diameter of the valve, m
E	The bulk modulus of elasticity, Pa
F	Damper shaft force, N
F_{damper}	Damper force, N
F_f	Friction force, N
F_{sky}	Skyhook force, N
h	Length of leakage gap, m
K_s	Spring constant, kg/s^2
K_t	Tire spring coefficient, kg/s^2
K_d	Derivative parameter constant
K_i	Integral parameter constant
K_P	Proportional parameter constant
m_g	Mass of the nitrogen gas, kg
M_s	Sprung mass, kg
M_u	Unsprung mass, kg
m_p	Floating piston mass, kg
N_s	Number of steps

P_c	Compression pressure, Pa
P_g	Gas pressure, Pa
P_{g0}	Initial gas pressure, Pa
P_{pv}	Piston valve pressure, Pa
P_r	Rebound pressure, Pa
P_{vf}	Foot valve pressure, Pa
Q_{lp}	The flow rate of leakage, m^3/s
Q_c	Fluid flow in the compression chamber, m^3/s
Q_{cr}	Fluid flows from the compression to rebound chamber
Q_{crv}	Fluid flows from the compression to reservoir chamber
Q_{rc}	Fluid flows from the rebound to compression chamber
Q_{rr}	Fluid flows from the reservoir to the compression chamber
Q_{sa}	The flow rate of the semi-active valve, m^3/s
Q_v	The flow rate of the piston valve, m^3/s
R	The radius of a rotary pin, m
R	Ideal gas constant, J/(K.mol)
r	The radius of the bleed orifice, m
t	Exposure duration, s
T	The temperature of the gas, K
V	Car forward velocity, m/s
V_c	The volume of the compression chamber, m^3
V_g	The volume of the gas chamber, m^3
V_{g0}	The initial volume of the gas chamber, m^3
V_r	The volume of rebound chamber, m^3
X	The direction of piston movement
X_r	Displacement of road excitation
X_s	Displacement of the sprung mass
X_u	Displacement of unsprung mass
$\dot{x}$	Piston velocity, m/s
$\dot{X}_s$	Stroke velocities of the front, m/s
$\dot{X}_u$	Stroke velocities of the rear, m/s
$\dot{X}_{def}$	Reference velocity, m/s
$\ddot{X}_s$	Stroke acceleration, m/s^2
y	Deflection of shim stack, m
ΔP	Change in pressure, Pa

ρ	The density of fluid, kg/m^3
μ	Viscosity, m^2/s
θ	Displacement angle, degree
α	Shaping filter
λ	Half wavelength, Hz
η	White noise

LIST OF ABBREVIATIONS

ADD	Acceleration Driven Damper
CAD	Computer-Aided Design
CAN	Controller Area Network
CES	Controlled Electronic Suspension
CFD	Computational Fluid Dynamics
CPU	Control Programming Unit
CVD	Continuously Variable Damping
ER	Electrorheological
IMU	Inertial Measurement Unit
FSI	Fluid-Structure Interaction
ISO	International Standard Organization
MEMS	Micro-Electro-Mechanical Systems
MSDV	Motion Sickness Dose Value
MR	Magnetorheological
NVH	Noise, Vibrations, and Harshness
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
RMS	Root Mean Square
SH-ADD	Mixed Skyhook-Acceleration Driven Damper
PID	Proportional-Integral-Derivative

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APPENDIX A
CAR SPECIFICATIONS

Table 5.1 Test vehicle information

Items	Specification	Remarks
Make/Model	Proton Persona SE	Year 2010 Reg No WTY4720 PL1CM6SRRAG269237
Powertrain	1.3L Campro IAFM 5M/T	Continental torque-based ECU
Suspension Type (Front)	Front McPherson strut with direct acting anti-roll bar	OE Damper supplier KYB
Suspension Type (Rear)	Rear Multilink with anti-roll bar	OE Damper supplier KYB
Tyre (Front)	Dunlop 175/70R13 (RE Spec)	Goodyear NCT5 175/70R13 (OEM Spec)
Tyre (Rear)	Dunlop 175/70R13 (RE Spec)	Goodyear NCT5 175/70R13 (OEM Spec)
Tyre Pressure	FR: 2.1 bar RR: 1.9 bar	Standard spec
Test Condition	4-up, full fuel. Variable test speeds and manoeuvres.	Test conditions to be adjusted accordingly.

Table 5.2 Center wheel to arc fender measurement

	Trim Height (mm)				**Trim Height (mm)**		**Spring Seat (mm)**		
Damper	**Kerb**		**4-up**		**Full Rebound**		**Height**		
Measurement	FL	FR	FL	FR	FL	FR	FL	FR	**Remarks**
	RL	RR	RL	RR	RL	RR	RL	RR	
OEM	375	370	355	345	435	435	204.3	204.5	Centre wheel to arc fender
	365	365	305	305	435	435	N/A	N/A	
ProRide TAP	370	365	355	355	430	430	204.4	204.3	Centre wheel to arc fender
	365	365	330	330	430	430	N/A	N/A	
Tuning #1	370	365	355	355	430	430	204.4	204.3	Centre wheel to arc fender
	365	365	330	330	430	430	N/A	N/A	
Tuning #2	370	365	355	355	430	430	204.4	204.4	Centre wheel to arc fender
	365	365	330	330	430	430	N/A	N/A	
Tuning #3	370	365	355	355	430	430	204.4	204.3	Centre wheel to arc fender
	365	365	330	330	430	430	N/A	N/A	
Tuning #4	370	365	355	355	430	430	204.4	204.3	Centre wheel to arc fender
	365	365	330	330	430	430	N/A	N/A	

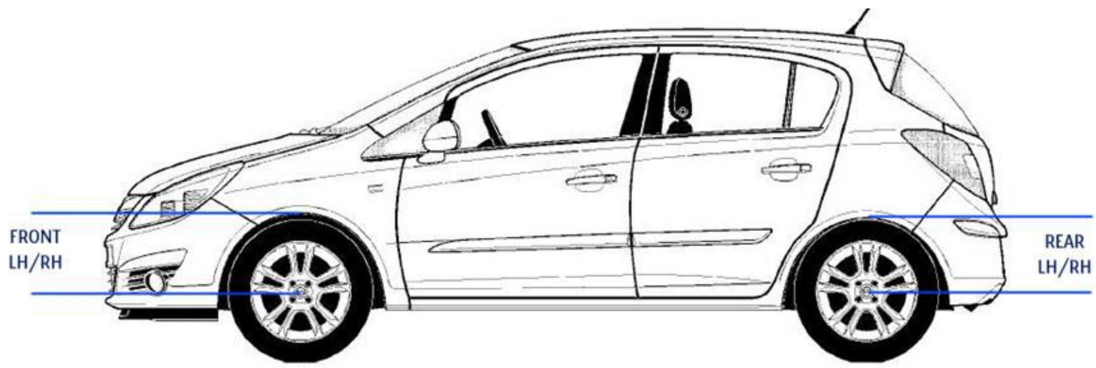

Figure A.1 Diagram shows the centre wheel to arch fender measurement

APPENDIX B
RIDE ROUTE/TEST TRACK

Straight-line:

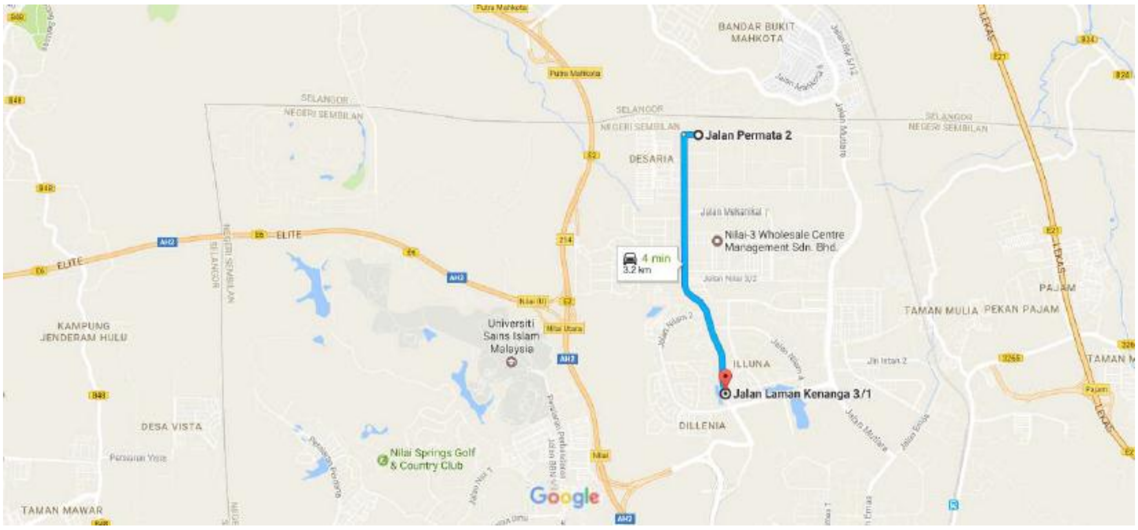

Figure B.2 Jalan Permata 2 to Jln Laman Kenanga 3/1, Nilai Impian, 71800 Nilai, Negeri Sembilan.

Roundabout:

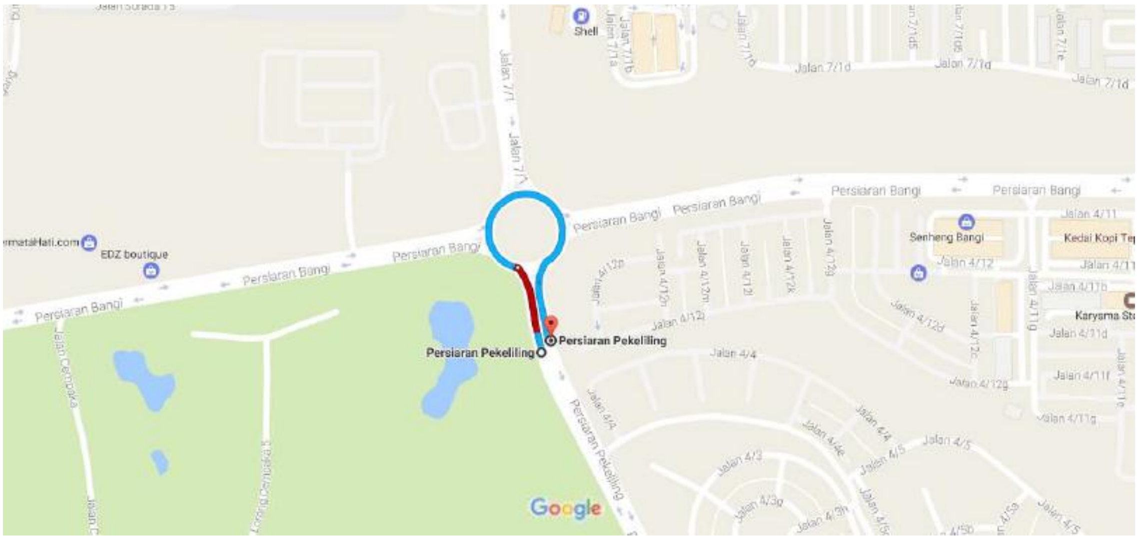

Figure B.3 12, Jalan 7/5, 43650 Bandar Baru Bangi, Selangor to Jalan 7/5, 43650 Bandar Baru Bangi, Selangor.

Bumpy:

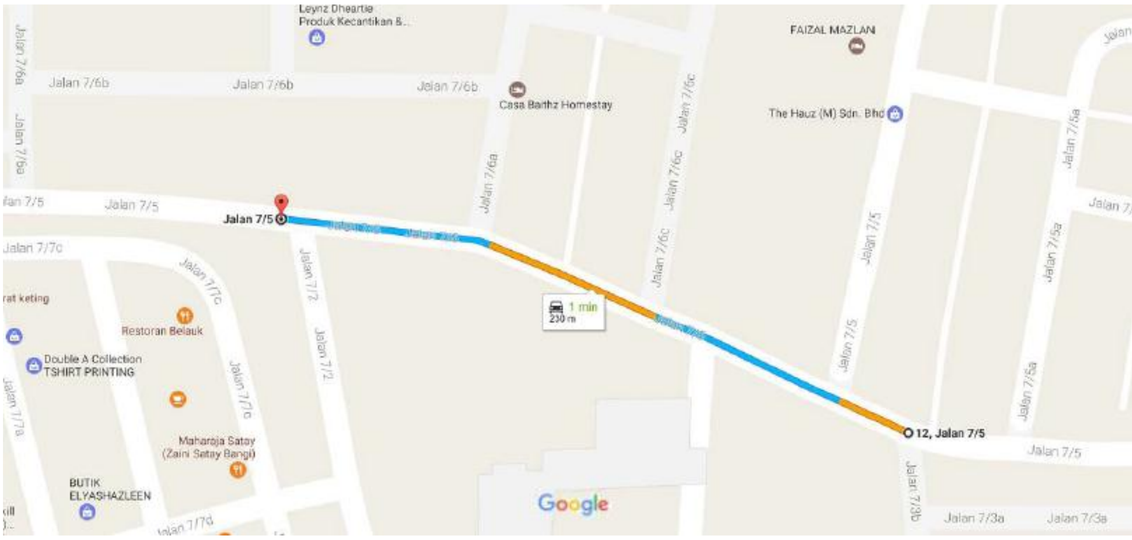

Figure B.4 12, Jalan 7/5, 43650 Bandar Baru Bangi, Selangor to Jalan 7/5, 43650 Bandar Baru Bangi, Selangor.

APPENDIX B
PUBLICATIONS

APPENDIX C1: 3rd International Conference on Automotive Innovative and Green Energy Vehicle (AIGEV, 2018).

Adjustable Valve Semi Active Suspension System for Passenger Car

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Abstract. The suspension of the car plays a very important role in the safety and the comfort of the vehicle and for absorbing the shock waves and give comfort for the driver and passenger. This paper improves the performance of automobile suspension system, by developing electronically adjustable semi active shock absorber. This achieved by attaching stepper motor for each shock absorber which helps in adjusting the bleed orifice to certain position that alternates the hydraulic oil flow in the shock absorber between piston's chamber during the process of compression and rebound. To evaluate the effect of developed semi active shock absorber on dynamic behavior of the vehicle, several tests were carried out on different types of road condition (bumpy, straight-line and roundabout). These tests were used to evaluate the acceleration and ride quality. There is great range in response when bleed orifice is opened reached up to 35% between the stiff and soft setting. The value of root means square acceleration (RMS) was calculated and compared with the standard of human exposure to whole body vibration, which shows slightly error of 6%. The result shows effect of electronically controllable shock absorber on vehicle's dynamic behavior. The advantage of electronics to improve performance of ride comfort and reduced the harms due to undesired vibration.

Keywords: Suspension; comfort; controllable; absorbers; softness.

APPENDIX C2: The International Conference on Recent Advances in Industrial Engineering and Manufacturing (ICRAIEM 2018**),** 12-13 December, Penang.

Numerical Investigation of Continuous Damping of the Semi-Active Suspension System for Passenger Car

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Abstract. The suspension of the car is considered an important element in the vehicle. The primary function of the suspension system is to isolate the vehicle structure from shocks and vibration due to irregularities of the road surface. There are two main objectives need to be satisfied which are: ride comfort and road handling. Ride comfort is inversely proportional to the absolute acceleration of the vehicle body, while the road handling is linked to the relative displacement between the vehicle body and the tires. This paper presented an attempted to enhance the performance of the shock absorber by developing a model of continuously variable damping (CVD). To evaluate the effect of the developed semi-active shock absorber on the dynamic behaviour of the vehicle, the model was analyzed and compared with the passive and On/Off sky-hook control strategy in the quarter car using two different types of road (random excitation, bumpy) as input to the quarter car model. Force hysteresis loop with different sets of orifice diameter was generated. The result indicates the CVD shows a reduction in both body acceleration and vertical displacement contrasting with passive and On/Off sky-hook 73.4% and 53.8% respectively and also the selling time by 79% and 59% for a bumpy road. This considered an improvement toward the ride comfort and vehicle stability. The simulated results for the quarter car model are shows similar trends and within range when compared with reference research paper.
Keywords: Vehicle Suspension System; CVD; controllable; absorbers; orifice.