

ห้องสมุดงานวิจัย สำนักงานคณะกรรมการวิจัยแห่งชาติ



E47302

การศึกษานิตยของคุณสมบัติของระบบบรรจุแบบผสม
ที่อธิบายบทบาทในการขับถ่ายของระบบบรรจุ

นางเกียรติกุล นาน้อย

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมเครื่องกล ภาควิชาวิศวกรรมเครื่องกล
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2553
ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย



E47302

การศึกษาผลของคุณสมบัติของระบบรองรับแบบแหนบ
ต่อความสบายในการขับขี่ของรถบรรทุกเล็ก



นางศิริธร แซ่เหล่ม

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมเครื่องกล ภาควิชาวิศวกรรมเครื่องกล
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2553
ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย



4 9 7 0 5 9 8 4 2 1

AN INVESTIGATION INTO THE EFFECTS OF LEAF SPRING SUSPENSION
PARAMETERS ON RIDE COMFORT OF LIGHT TRUCKS

Mrs. Sirithon Saelem

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Mechanical Engineering

Department of Mechanical Engineering

Faculty of Engineering

Chulalongkorn University

Academic Year 2010

Copyright of Chulalongkorn University

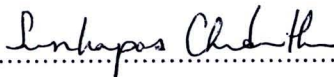
Thesis Title	AN INVESTIGATION INTO THE EFFECTS OF LEAF SPRING SUSPENSION PARAMETERS ON RIDE COMFORT OF LIGHT TRUCKS
By	Mrs. Sirithon Saelem
Field of Study	Mechanical Engineering
Thesis Advisor	Assistant Professor Sunhapos Chantranuwathana, Ph.D.
Thesis Co-Advisor	Nuksit Noomwongs, D.Eng.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial
Fulfillment of the Requirements for the Master's Degree

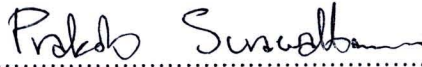
.....Dean of the Faculty of Engineering
(Associate Professor Boonsom Lerdhirunwong, Dr.Ing.)

THESIS COMMITTEE

..... Chairman
(Assistant Professor Witaya Wannasuphoprasit, Ph.D.)

..... Thesis Advisor
(Assistant Professor Sunhapos Chantranuwathana, Ph.D.)

..... Thesis Co-Advisor
(Nuksit Noomwongs, D.Eng.)

..... External Examiner
(Associate Professor Prakob Surawattanawan, Ph.D.)

ศิริธร แซ่เหล่ม : การศึกษาผลของคุณสมบัติของระบบรองรับแบบแหนบต่อความสบายในการขับขี่ของรถบรรทุกเล็ก. (AN INVESTIGATION INTO THE EFFECTS OF LEAF SPRING SUSPENSION PARAMETERS ON RIDE COMFORT OF LIGHT TRUCKS) อ. ที่ปรึกษาวิทยานิพนธ์หลัก : ผศ.ดร.สันหพศ จันทรานูวัฒน์, อ. ที่ปรึกษาวิทยานิพนธ์ร่วม : อ.ดร.นักสิทธิ์ นุ่มวงษ์, 105 หน้า.

E47302

ในงานวิจัยนี้ แบบจำลองของสปริงแหนบได้ถูกสร้างขึ้นเพื่อใช้ศึกษาผลของคุณสมบัติของระบบรองรับแบบแหนบต่อความสบายในการขับขี่ของรถบรรทุกเล็ก ซึ่งมีวัตถุประสงค์หลักคือการสร้างแบบจำลองของสปริงแหนบที่ประกอบด้วยพารามิเตอร์ที่สามารถนำไปใช้ในการออกแบบเพื่อผลิตสปริงแหนบและเพื่อใช้สำหรับการทำนายระดับค่าความสบายในการขับขี่ แบบจำลองที่ถูกสร้างขึ้นนี้จะถูกตรวจสอบความถูกต้องโดยเปรียบเทียบผลที่ได้จากการจำลองปัญหากับผลที่ได้จากการทดลองจริงด้วยชุดแท่นทดสอบแหนบที่สามารถวัดระยะการเคลื่อนที่ภายใต้สภาวะการรับแรงแบบคงที่

แบบจำลองของสปริงแหนบที่ได้รับการตรวจสอบความถูกต้องแล้ว จะถูกนำไปใช้เพื่อศึกษาผลของพารามิเตอร์ของสปริงแหนบต่อค่าความสบายในการขับขี่ของรถบรรทุกเล็กด้วยแบบจำลองระบบรองรับของยานพาหนะแบบหนึ่งในสี่ และในการจำลองแบบปัญหานั้น พารามิเตอร์บางตัวที่ใช้ในการออกแบบสปริงแหนบได้แก่คุณสมบัติของโคงเตงแหนบ (shackle) ถูกนำมาพิจารณาและหาความสัมพันธ์ต่อค่าความสบายในการขับขี่ด้วยวิธีคำนวณตามมาตรฐาน ISO 2631-1 ที่ค่าพารามิเตอร์ต่างๆของสปริงแหนบและชนิดของแบบจำลองของถนนที่ถูกสร้างขึ้นภายใต้สภาวะความเร็วคงที่ ผลจากการทดลองพบว่า ค่าความสบายในการขับขี่จะดีกว่าเมื่อถนนเรียบ ซึ่งค่าจะค่อยๆเปลี่ยนแปลงเมื่อเปลี่ยนชนิดของถนนจากเรียบ(very good) ไปสู่ ถนนขรุขระ(poor) แต่จะเพิ่มขึ้นอย่างฉับพลันเมื่อเปลี่ยนชนิดของถนนจากถนนขรุขระไปสู่ถนนขรุขระมาก(very poor) นอกจากนี้ยังพบว่าค่าความสบายในการขับขี่จากการทดลองด้วยแบบจำลองของระบบรองรับที่มีสปริงแหนบแบบไม่เชิงเส้นและแบบเชิงเส้นนั้นมีความแตกต่างกัน จึงสรุปได้ว่าแบบจำลองของสปริงแหนบที่สร้างขึ้นนี้มีผลอย่างมีนัยสำคัญต่อค่าความสบายในการขับขี่

ภาควิชา.....วิศวกรรมเครื่องกล.....ลายมือชื่อนิสิต..... *Dr. Mr.*

สาขาวิชา.....วิศวกรรมเครื่องกล.....ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก..... *อ.ดร.สันหพศ จันทรานูวัฒน์*

ปีการศึกษา 2553ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์ร่วม..... *อ.ดร.นักสิทธิ์ นุ่มวงษ์*

4970598421 : MAJOR MECHANICAL ENGINEERING

KEYWORDS : LEAF SPRING MODEL / DESIGN PARAMETERS / RIDE COMFORT

SIRITHON SAELEM : AN INVESTIGATION INTO THE EFFECTS OF LEAF
SPRING SUSPENSION PARAMETERS ON RIDE COMFORT OF LIGHT
TRUCKS. THESIS ADVISOR : ASSISTANT PROFESSOR SUNHAPOS
CHANTRANUWATHANA, Ph.D., THESIS CO-ADVISOR : NUKSIT
NOOMWONGS, D.Eng., 105 pp.

E47302

A simulation-based leaf spring model was created to study the effect of leaf spring suspension parameters on vehicle ride comfort. The main objective is to build a simulation model for ride comfort prediction from leaf spring parameters which can be used in design process. In this research, an experimental leaf spring model was verified by using a leaf spring test rig that can measure vertical static deflection of leaf spring under static loading condition.

The verified model was then used to study the effect of leaf spring parameters on ride comfort of a light truck, using a simple 2-degree-of-freedom quarter-car model. In simulation, some design parameters of leaf spring, including the effect from shackle was applied, and the relationship between ride comfort performance (ISO2631-1) and variations in leaf spring design parameters were obtained upon different types of synthetic road irregularity profiles at constant velocity. The overall results show that ride comfort is better on smooth road with gradual changes from "very good" to "poor" road and sudden increase for "very poor" road. The values obtained from the proposed leaf spring model are different from those of the linear leaf spring model's. Hence, it can be concluded that the proposed leaf spring model has significant effects on vehicle ride comfort.

Department :Mechanical Engineering.....

Student's Signature *Sirithon Saelem*

Field of Study :Mechanical Engineering.....

Advisor's Signature *Sunhapos Chantranuwathana*

Academic Year : 2010

Co-Advisor's Signature *Nuksit Noomwongs*

ACKNOWLEDGEMENTS

First of all, Most of values and success must be dedicated to my supervisor, Asst. Prof Dr. Sunhapos Chantranuwathana who has supported me throughout my thesis with his patience and knowledge. For many years of study, he has devoted his time to provide advice and also brought me a lot of perspective vision in solving problems.

I am also grateful for my co-advisor, Dr. Nuksit Noomwongs for his advice and valuable recommendations, especially for the inspirations on the alternative methods of leaf spring modeling.

Great admiration for a senior project team who has changed ideas and theory into a very useful leaf spring test rig, a very important element in research completion. During the time of works, I have been aided by friends and the university staffs. They are very kind and helpful. I am grateful for the Department of Mechanical Engineering who has provided the support and equipment I have needed to produce and complete my thesis.

Final words, I would like to give a special thank to my family for all kind of support, encouragement and love, especially for my husband who has offered me on financial support and encouraged me to complete this work. My deeply regards to my beloved grandmother who has passed away in the very hard moment when this thesis was being carried on

CONTENTS

TITLE	PAGE
ABSTRACT (THAI).....	IV
ABSTRACT (ENGLISH).....	V
ACKNOWLEDGEMENTS.....	VI
CONTENTS.....	VII
LIST OF TABLES.....	XI
LIST OF FIGURES.....	XII
LIST OF ABBREVIATIONS.....	XVI
CHAPTER I INTRODUCTION.....	1
1.1. Research Background.....	1
1.2. Research Objective.....	2
1.3. Scope of the Research.....	2
1.4. Obtained Results.....	2
1.5. Research Operating Structure.....	3
1.6. Outline of the Thesis.....	3
CHAPTER II LITERATURE REVIEW.....	5
2.1. Ride Comfort.....	5
2.1.1. Definitions.....	6
2.1.2. Ride Characteristic of Vehicles.....	7
2.1.3. Application of Ride Comfort in Automotive Field.....	8
2.1.4. Ride Comfort Measurement.....	10
2.1.4.1. Objective Measurement.....	12
2.1.4.2. Subjective Measurement.....	12
2.1.5. Ride Comfort Standards.....	14
2.1.5.1. ISO 2631–1 General Requirements.....	16
2.1.5.2. Basic Ride Comfort Evaluation Methods.....	16

2.1.5.2.1. Power Spectral Density (PSD) Analysis.....	16
2.1.5.2.2. RMS Accelerations.....	18
2.1.5.2.3. Frequency–Based Weighting Technique of Acceleration Spectra.....	18
2.2. Leaf Spring.....	20
2.2.1. Characteristic of Leaf Spring.....	25
2.2.2. Interleaf Friction and Stick-slip Phenomena.....	26
2.2.3. Shackle Effects.....	27
CHAPTER III RESEARCH METHODOLOGY.....	29
3.1. Description of Research Procedure.....	29
3.2. Research Tools.....	30
3.2.1. Field Experiment Tools.....	31
3.2.2. Simulation Tools.....	31
3.3. Methodology.....	31
3.3.1. Data Collecting.....	31
3.3.1.1. Measured quantities.....	32
3.3.1.2. Sensor Positioning.....	32
3.3.2. Data Analysis.....	33
3.3.2.1. Time Domain Analysis.....	33
3.3.2.2. Frequency Domain Analysis.....	33
3.4. Summary of Research Approach.....	34
CHAPTER IV PRELIMINARY TEST.....	36
4.1. Objective.....	36
4.2. Test Instruments.....	36
4.3. Tested Vehicle.....	37
4.4. Sensors positioning.....	38
4.5. Testing Locations.....	39
4.6. Driving Conditions.....	39

4.7. Procedure.....	39
4.8. Data Analysis.....	42
4.8.1. Time Domain Analysis.....	42
4.8.2. Frequency Domain Analysis.....	42
4.9. Results.....	42
4.9.1. Results of Time domain Analysis.....	43
4.9.2. Results of Frequency domain Analysis.....	44
4.9.3. Results of Frequency Weighting Analysis.....	49
4.10. Conclusions and Further Recommendations.....	53
 CHAPTER V LEAF SPRING MODELING AND VERIFICATION.....	54
5.1. Leaf Spring Modeling.....	54
5.1.1. Existing Leaf Spring Models.....	55
5.1.1.1. Classical Beam Theory.....	55
5.1.1.2. Finite-Element Method.....	56
5.1.1.3. Multibody Kinematic.....	56
5.1.1.4. The Three Link Equivalent Model.....	56
5.1.2. Friction Model and Hysteresis Effects.....	57
5.1.3. Description of the Leaf Spring Model.....	57
5.1.4. The Full Leaf Spring Model Construction.....	59
5.2. Verification of the Leaf Spring Model.....	62
5.2.1. Design and Construction of the Leaf Spring Test Rig.....	62
5.2.1.1. Test Rig Frame.....	62
5.2.1.2. Load Measuring Unit.....	63
5.2.1.3. Deflection Measuring Unit.....	64
5.2.2. Verification Testing.....	64
5.2.3. Parameters Identification.....	68
 CHAPTER VI SIMULATION OF SUSPENSION MODEL AND PARAMETRIC STUDY INTO THE EFFECTS ON RIDE COMFORT.....	71

6.1. Quarter–Car Model.....	71
6.1.1. Model Characteristics.....	72
6.1.2. Mathematical Equations of the Model.....	73
6.2. Road Input Profile.....	73
6.3. Completed Vehicle Suspension Model.....	75
6.4. Parametric Study by Simulation.....	75
6.5. Ride Comfort Results from Simulating Model Subjected to Random White- Noise Input.....	78
6.6. Discussion of Results and Conclusion.....	89
 CHAPTER VII DISCUSSION OF THE RESULTS AND CONCLUSION.....	91
7.1. Summary of the Research.....	91
7.2. Conclusion.....	92
7.3. Further Recommendations.....	92
 REFERENCES.....	94
 APPENDICES.....	96
APPENDIX A.....	97
PRINCIPAL FREQUENCY WEIGHTINGS IN ONE-THIRD OCTAVES.....	98
APPENDIX B.....	100
DEFINITION OF VEHICLE'S COORDINATE SYSTEM.....	101
APPENDIX C.....	102
MATLAB M-FILE CODE.....	103
 BIOGRAPHY.....	105

LIST OF TABLES

TABLE	PAGE
Table 2–1 ISO 2631 approximate comfort/discomfort scale based on magnitude of overall vibration.....	15
Table 4–1 Technical information of the tested vehicle.....	37
Table 4–2 The weighted RMS accelerations results.....	51
Table 5-1 Experimental result of leaf spring deflection subjected to vertical applied load.....	66
Table 6-1 Parameters of the simulated quarter-car model.....	75
Table 6-2 The weighted RMS accelerations, representing the level of ride comfort/ discomfort subjected to different classes of roads (non-linear suspension)	79
Table A-1 Principal frequency weightings in one-third octaves.....	98

LIST OF FIGURES

FIGURE	PAGE
Fig.2-1 The vibration isolation property of vehicle suspension.....	8
Figs.2-2(a) – (b) Recommended vibration tolerance limits of a seated person based on different studies.....	9
Fig.2-2(c) The discomfort boundary contour based on vertical floor accelerations	10
Fig.2-3 Ride comfort model.....	11
Fig.2-4(a) SAE recommended practice for subjective rating scale for evaluation of noise and ride comfort characteristics related to motor vehicle tires	13
Fig.2-4(b) Subjective rating scale with separated opinion questions on property of vehicle component.....	13
Fig.2-4(c) Schedule of the “couple by couple” method to rank 12 different vehicles.....	13
Fig.2-5 Standard criteria limits as a function of frequency and exposure time for vibration in vertical direction.....	15
Fig.2-6 Frequency weighting curves for the principle weightings.....	20
Fig.2-7 Leaf spring components and construction.....	21
Figs.2-8(a) – (d) Different design of leaf spring eyes.....	22
Fig.2-9 Center bolt.....	22
Fig.2-10 Rebound clips.....	23
Figs.2-11(a) – (d) Types of leaf spring ends.....	24
Fig.2-12(a) – (f) Leaf spring configurations.....	24
Fig.2-13(a) – (b) Single and variable rate leaf spring.....	25
Fig.2-14 Load–deflection diagram of tested leaf spring.....	26
Figs.2-15(a) – (b) the Leaf spring configuration at installation.....	27
Fig.3-1 Schematic diagram of working procedure.....	29
Fig.3-2 Basicentric axes of a seated person, adapted from ISO 2631-1.....	32
Fig.4-1 The tested vehicle used in the investigation.....	37
Fig.4-2(a) position of sensors installed within a cabin.....	38

Fig.4-2(b) Positions of sensors installed outside a cabin.....	38
Fig.4-2(c) Attachment of a video camera.....	39
Fig.4-3 Different driving situation of test tracks.....	41
Fig.4-4(a) Acceleration results of driving situation case 1 captured by two different sensors installed within a cabin.....	45
Fig.4-4(b) Acceleration results of driving situation case 6 captured by two different sensors installed within a cabin.....	46
Fig.4-5 Rotational acceleration results of driving situation case 1 and case 2 captured by X-BOW (six-axis) sensor.....	47
Fig.4-6 Vertical acceleration results of driving situation case 1 captured by two different sensors installed outside a cabin.....	48
Fig.4-7 PSD results of acceleration spectra for driving situation case1 and case 6 captured by two different sensors installed within a cabin.....	49
Fig.4-8 graphic results of weighted RMS accelerations.....	52
Fig.5-1 Symmetrical multi-leaf spring with design parameters.....	55
Fig.5-2 Five link mechanism of a leaf spring model.....	58
Fig.5-3 Equivalent linkage of the upturned eye cantilever spring.....	58
Fig.5-4 Full leaf spring model, regarding hysteresis effects.....	60
Fig.5-5 Hysteresis component of a leaf spring model.....	61
Fig.5-6 Final design of the test rig frame.....	62
Fig.5-7 Configuration of the leaf spring test rig.....	63
Fig.5-8 The guide base for load cell and force-actuator attachment.....	63
Fig.5-9 The LVDT measuring unit.....	64
Fig.5-10 Five link mechanism of a leaf spring model.....	65
Fig.5-11 The animated results of simulated model.....	65
Fig.5-12 The load-deflection curve result obtained from test rig experiment.....	67
Fig.5-13 The load-deflection curve of torque and angular displacement	67
Fig.5-14 Load-deflection curve result of linear leaf spring model.....	68
Fig.5-15 Load-deflection curve of force (kg) and displacement (cm).....	69

Fig.5-16 Comparison between load-deflection curve results from experiment and simulation.....	69
Fig.6-1 Conceptual design of the quarter-car model for suspension system.....	72
Fig.6-2 Road surface roughness classification by ISO.....	74
Fig.6-3 The result of simulated road inputs compared with the classification standard.....	74
Fig.6-4 A simple road model used to simulate road inputs.....	75
Fig.6-5 Completed vehicle suspension model.....	77
Fig.6-6 The relationship between torque and angular displacement at the rotational joints.....	78
Fig.6-7 The relationship between torque and angular displacement obtained from linear-leaf spring suspension model.....	78
Fig.6-8(a) The plots of RMS vertical acceleration of vehicle suspension at 60° of shackle angle.....	80
Fig.6-8(b) The plots of RMS vertical acceleration of vehicle body (cross line) and tire (circle line) at 60° of shackle angle.....	80
Fig.6-9(a) The plots of RMS vertical acceleration of vehicle suspension at 90° of shackle angle.....	81
Fig.6-9(b) The plots of RMS vertical acceleration of vehicle body (cross line) and tire (circle line) at 90° of shackle angle.....	81
Fig.6-10 Ride comfort results of nonlinear and linear model at shackle angle 60°	82
Fig.6-11 Ride comfort results of nonlinear and linear model at shackle angle 70°	83
Fig.6-12 Ride comfort results of nonlinear and linear model at shackle angle 80° ...	83
Fig.6-13 Ride comfort results of nonlinear and linear model at shackle angle 90° ...	84
Fig.6-14 Ride comfort results of nonlinear and linear model at shackle angle 110° ..	84
Fig.6-15 Ride comfort results of nonlinear and linear model at shackle angle 120° ..	85
Fig.6-16(a) Ride comfort results of nonlinear leaf spring model at different shackle angles.....	86
Fig.6-16(b) Ride comfort results of nonlinear leaf spring model for "very good" to "average" road.....	87

Fig.6-17 Ride comfort results of nonlinear leaf spring model at different classes
of roads..... 87

Fig.6-18 Ride comfort level of nonlinear leaf spring model at different classes of
roads..... 88

Fig.6-19 Symmetrical leaf spring with shackle..... 90

Fig.B-1 Definition of vehicle coordinate system..... 101

LIST OF ABBREVIATIONS

Terms, Abbreviations and Acronyms	Meaning
CG	Centre of gravity. The center of gravity is the average location of the weight of an object. The point at which a body's mass may be said to be concentrated for purposes of determining forces on that body.
f	Frequency (Hertz)
g	Acceleration due to gravity at earth's surface (9.81 m/s^2)
L	The distance between leaf spring eyes, representing full span length of leaf spring subjected to zero loading.
m_b /Sprung Mass	The sprung mass is the portion of the vehicle's total mass that is supported above the suspension. The sprung weight typically includes the body, frame, the internal components, passengers, and cargo, but does not include the mass of the components suspended below the suspension components such as wheels, axles and brakes.
m_w /Unsprung Mass	The unsprung mass is the mass of the various parts of a vehicle that are not carried on the springs, such as wheels, axles, and brakes.
PSD	Power Spectral Density
Ride	Ride or ride quality is quantified by acceleration measured at vehicle body while traveling on road.
RMS	Root mean square value
SAE	the Society of Automotive Engineers
Shackle	Shackle is a swinging link that connect a leaf spring with the vehicle frame to provide more degree of freedom when the leaf spring is moving under applied load.

Terms,Abbreviations and Acronyms	Meaning
α	Shackle angle (rad)
x_g / Suspension stroke	The approximated suspension stroke or suspension displacement applied in this research is the absolute displacement of the sprung mass compared to the unsprung mass which represents vehicle ride's height upon different type of road irregularities.
x_g /Spring Deflection	The distance that a spring travels under a compressive force, measured at CG point of the leaf spring
Y/Camber Height (cm)	The leaf spring's arc length measured at axle's seat