MULTILAYERS PREISACH MODEL FOR MAGNETORHEOLOGICAL ELASTOMER (MRE) MODELLING OPTIMIZED WITH PARTICLE SWARM OPTIMIZATION (PSO) AND PID-SKYHOOK CONTROL OF AN ACTIVE FRONT BUMPER SYSTEM

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**MASTER OF SCIENCE
(MECHANICAL ENGINEERING)**

**UNIVERSITI PERTAHANAN NASIONAL
MALAYSIA**

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Thesis submitted to the Centre for Graduate Studies, Universiti Pertahanan Nasional Malaysia, in fulfilment of the requirements for the Degree of Master of Science (Mechanical Engineering)

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ABSTRACT

In this study, an active front bumper device is designed to reduce the impact on a vehicle in the case of a road accident. Road accidents can inflict harm on an automobile's body, especially on the front bumper, which is referred to as a crumple zone and can injure passengers. In order to reduce the effect of a frontal collision, an active front bumper system based on the Magnetorheological elastomer (MRE) isolator was developed. This is a result of MRE's exceptional ability to absorb impact force in the presence of a magnetic field. Therefore, the goal of this work is to create a mathematical model of a real vehicle's crumple zone, analyze the dual-acting MRE isolator's impact behavior, and create a control strategy for assessing the MRE isolator's impact behavior in three different types of impact collisions which are light, medium, and hard. The initial stage of the methodology was the development of a mathematical model that represents the crumple zone. This model is developed using Multiple Kelvin Model (MKM) that consists of seven mass-spring-damper systems. The model is optimized for the parameters of spring stiffness, *k* and damping coefficient, *c* using Particle Swarm Optimization (PSO) methods. This optimization process is conducted in order to compare the simulation outcomes with the experimental results obtained from Actual Crash Data (ACD). Subsequently, a double acting Magnetorheological Elastomer isolator is fabricated and simulated using a Multi-Layer Preisach model to characterize the impact behavior of a double acting MRE isolator. Next, the model is validated using experimental data from drop impact tests on MRE samples with the various currents ranging from 0-2 A and trained using PSO. In addition, an interpolate model of the MRE isolator is used to predict the 0.3, 0.7, 1.3, and 1.7 A force and displacement characteristics for the intermediate current. Furthermore, the best performance of the control structure can be achieved by using a combination of controllers such as Proportional-Integral-Derivative (PID) and skyhook controller for the active front bumper model. The present study investigates the efficacy of the suggested control system in attaining the desired force during impact collisions across three distinct scenarios which are light impact (83.25 kN), medium impact (333.02 kN), and heavy impact (749.28 kN). The vehicle test rig is utilized to conduct experiments using varying masses of impactors in order to obtain measurements of acceleration and displacement. The implementation of the active front bumper system has demonstrated a significant reduction in the magnitude of frontal collisions. Specifically, the system has achieved a reduction of 50.71%, 47.32%, and 33.47% in acceleration results, and 50.00%, 26.96%, and 13.80% in displacement results. These outcomes have been seen across three distinct impact force cases, namely light, medium, and strong collisions.

ABSTRAK

Dalam kajian ini, sebuah sistem bumper hadapan aktif telah direka untuk mengurangkan impak pada bahagian hadapan kenderaan ketika terlibat dalam kemalangan jalan raya. Kemalangan jalan raya boleh menyebabkan kerosakkan terhadap badan kenderaan, terutamanya pada bumper hadapan yang dikenali sebagai zon renyuk yang boleh mengancam nyawa penumpang. Bagi mengurangkan kesan perlanggaran hadapan, sistem bumper hadapan aktif berasaskan isolator Magnetorheological elastomer (MRE) telah dibangunkan. Ini adalah hasil daripada keupayaan luar biasa MRE yang mampu menyerap daya impak dengan kehadiran medan magnet. Oleh itu, objektif kajian ini adalah untuk mencipta sebuah model matematik zon renyuk berdasarkan kenderaan sebenar bagi menganalisis tingkah laku impak isolator MRE dwi tindakan, dan merangka strategi kawalan yang berkesan untuk menilai tingkah laku impak isolator MRE dalam tiga tahap perlanggaran yang berbeza iaitu ringan, sederhana, dan kuat. Fasa awal metodologi adalah pembangunan model matematik yang mewakili zon renyuk kenderaan. Model ini direka menggunakan pendekatan Kelvin-Voigt tunggal yang ditingkatkan menjadi tujuh darjah kebebasan jisim-pegas-peredam. Parameter model ini yang terdiri daripada (k) dan (c) dioptimumkan menggunakan kaedah Particle Swarm Optimization (PSO). Proses pengoptimuman ini dijalankan untuk membandingkan hasil simulasi dengan hasil ujian perlanggaran sebenar yang diperoleh dari Actual Crash Data (ACD). Seterusnya, isolator Magnetorheological elastomer (MRE) dwi tindakan dibina dan disimulasikan menggunakan model Multi-Layer Presaich untuk meramalkan tingkah laku impak isolator MRE dwi tindakan. Kemudian, model ini disahkan dengan data

dari ujian impak jatuh ke atas sampel MRE dengan arus yang berlainan dari 0-2 A yang dilatih menggunakan PSO. Selain itu, model interpolasi isolator MRE digunakan untuk meramalkan ciri-ciri daya dan anjakan pada arus pertengahan iaitu 0.3, 0.7, 1.3, dan 1.7 A. Tambahan pula, prestasi terbaik sistem bumper hadapan aktif dapat dicapai dengan menggunakan gabungan pengawal yang terdiri daripada Proportional-Integral-Derivative (PID) dan skyhook. Kajian ini telah membuktikan keberkesanan sistem kawalan yang dicadangkan dalam mencapai daya yang diinginkan semasa perlanggaran impak di tiga senario yang berbeza iaitu impak ringan (83.25 kN), impak sederhana (333.02 kN), dan impak kuat (749.28 kN). Rig ujian pelanggaran digunakan untuk menjalankan eksperimen dengan menggunakan pelbagai jisim pengimpak bagi mendapatkan ukuran pecutan dan anjakan. Pelaksanaan sistem bumper hadapan aktif telah menunjukkan pengurangan yang ketara dalam magnitud perlanggaran hadapan. Secara khususnya, sistem ini telah mencapai pengurangan sebanyak 50.71%, 47.32%, dan 33.47% dalam keputusan pecutan. Manakala, dalam keputusan anjakan adalah 50.00%, 26.96%, dan 13.80%. Pemerhatian ini telah dijalankan di tiga daya pelanggaran yang berbeza, iaitu perlanggaran ringan, sederhana, dan kuat.

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APPROVAL

The Examination Committee has met on **26 February 2024** to conduct the final examination of **‘Alawiyah Hasanah Binti Mohd Alawi** on his degree thesis entitled **‘Multilayers Preisach Model for Magnetorheological Elastomer (MRE) Modelling Optimized with Particle Swarm Optimization (PSO) and PID–Skyhook Control of An Active Front Bumper System’.**

The committee recommends that the student be awarded the of Master of Science (Mechanical Engineering).

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Academic session	: 2023/2024

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LIST OF ABBREVIATIONS

ABS	-	Antilock Braking System
ACD	-	Actual Crash Data
ADAMS	-	ADAMS Multibody Model
ADAS	-	Advanced Driver Assistance Systems
AEB	-	Automatic Emergency Braking
BPF	-	Band Pass Frequency
CFRP	-	Carbon Fibre Reinforced Polymer
CIP	-	Carbonyl Iron particle
DOF	-	Degree of Freedom
E&E	-	Elkady and Elmarakbi Model
ECU	-	Electronic Control Unit
FCW	-	Forward Collision Warning
GFRP	-	Glass Fibre Reinforced Polymer
HPF	-	High Pass Frequency
IMC	-	Internal Model Control
LB	-	Lower Boundary
LPF	-	Low Pass Frequency
LVDT	-	Linear Variable Differential Transformer
MIROS	-	Malaysian Institute of Road Safety Research
MKM	-	Multiple Kelvin Model
MR	-	Magneto – Rheological
MRE	-	Magnetorheological Elastomer
MREBEARD	-	Adaptive Energy Absorption Device

MRF	-	Magneto – Rheological Fluid
PET	-	Polyethylene Terephtalate
PID	-	Proportional-Integral-Derivative
POM	-	Polyoxymethylene
PSO	-	Particle Swarm Optimization
PWM	-	Pulse Width Modulation
RMSE	-	Root Mean Square Error
RTV	-	Room Temperature Vulcanization
UB	-	Upper Boundary
UPNM	-	Universiti Pertahanan Nasional Malaysia
VTB	-	Vehicle to Barrier
VTV	-	Vehicle to Vehicle

LIST OF SYMBOLS

c	-	Damper Coefficient
C_1	-	Skyhook Damper Coefficient
F	-	Impact Force
F_d	-	Force Desired
F_r	-	Froude Number
g	-	Gravitational Acceleration
iw	-	Inertia weight
k	-	Spring Constant
K	-	Potential Energy
K_d	-	Derivative Value
K_i	-	Integral Value
K_p	-	Proportional Value
L	-	Length of Vehicle
N_i	-	Number of Iterations
N_p	-	Number of Particles
Q	-	Dissipative Energy
T	-	Kinetic Energy

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Road safety remains a significant national concern in Malaysia, with an increase in road accident cases to approximately 53,000 in 2022. Tragically, these incidents have resulted in the loss of over 12,000 lives, as reported by The Sun (The Sun, 2024). One major contributing factor to these accidents is the design of the bumper beam. They are designed with a conventional bumper beam that is less efficient in terms of absorbing the total amount of energy during a frontal collision. This conventional bumper beam is constructed from hard composites and can only absorb a small amount of impact energy. Furthermore, this type of bumper does not actively reduce the impact force and is designed to withstand low-speed collisions where the impact force is minimal. Consequently, this design flaw often leads to unnecessary vehicle damage during collisions.

Therefore, this study is focused on improving the safe protection of the occupants from the frontal collision by introducing an active front bumper system employing Magnetorheological Elastomer (MRE) dampers positioned between the chassis and the front bumper. MRE is a well-known material that has the capability to adjust its stiffness and damping coefficients with the applied currents injected to the material. Initially, a mathematical model representing an actual vehicle crumple zone is developed to examine which part of the vehicle affected during frontal collision (Amin et al., 2017; Ramamurthy etal.,2018).

Moreover, a simulation model is developed to simulate the impact behaviour of Magnetorheological Elastomer aiming to characterize its force-displacement during impact collision. Next, the proposed model undergoes validation through comparison with experimental results obtained from a drop impact test by comparing the force displacement characteristics with the different applied current. Both validated models are then used in the control strategy to evaluate the active front bumper system.

The control strategy implemented in this study analyses the system's response in three responses which are displacement, acceleration, and transmitted force using the hybrid controller. This evaluation is then continued with the fabrication of a collision test rig that represents the active front bumper system. The experiment is conducted at different cases such as passive, active, and off state to evaluate the active front bumper system in reducing the effect of frontal collision than compared with the simulation result (Sethi M.K. & Kumar A, 2016; Leng D et al., 2017).

1.2 Problem Statement

Road accident cases have shown an increase about 175,000 cases from 2021 to 2022, particularly involving frontal vehicle collisions compared to rear and side collisions (The Star, 2023). This trend can be attributed to the conventional bumper