# MODIFIED KAMAL MODEL FOR CRUMPLE ZONE BEHAVIOR AND CONTROL OF ACTIVE FRONT BUMPER SYSTEM FOR HEAD-ON COLLISION

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**(MECHANICAL ENGINEERING)**

**UNIVERSITI PERTAHANAN NASIONAL MALAYSIA**

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**AMRINA RASYADA BINTI ZUBIR**

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)

**2024**

# ABSTRACT

The development of an active front bumper system arose from the realization that the conventional bumpers are insufficient in absorbing impact energy during frontal collisions. This system utilizes magnetorheological elastomers (MREs), which can adjust its stiffness and damping properties in response to a magnetic field, thus significantly enhancing the impact absorption capabilities. The objective of this project is to model the dynamics of crumple zone, to model the impact behavior of the dual-acting MRE damper and to develop a control strategy for active front bumper system that can reduce the effects of impact force due to collision. The methodology of this study is started with developing a 6 degree-of-freedom (DOF) vehicle crash model based on Kamal approach that represent the actual vehicle crumple zone. Next, the fabrication of dual-acting MRE damper takes place where the impact behavior of the MRE is modelled using $4^{th}$ order polynomial to study for its force-displacement characteristics. Furthermore, the collision test rig is developed for evaluating the performance of the active front bumper system by conducting the experiment at different levels of collisions including light (83.25 kN), medium (333.02 kN) and hard (749.28 kN). Besides, the combination of proportional-integral-derivative controller (PID) and skyhook controller are chosen to be implemented in the active front bumper system. The proposed method has effectively reduced the impact of frontal collision by 63.78%, 44.16% and 30.06% in terms of acceleration. While, for displacement the reduction are 55.56%, 37.54% and 19.33% for light, medium and hard impact respectively.

# ABSTRAK

Pembangunan sistem bampar hadapan yang aktif adalah disebabkan oleh kekurangan bampar lazim dalam menyerap tenaga hentaman semasa perlanggaran hadapan. Sistem ini menggunakan magnetorheological elastomer (MRE), yang boleh melaraskan sifat kekakuan dan redamannya sebagai tindak balas kepada medan magnet, dengan itu meningkatkan keupayaan penyerapan impak dengan ketara. Objektif projek ini adalah untuk memodelkan dinamik zon renyuk, memodelkan tingkah laku impak peredam MRE dwi-tindakan dan membangunkan strategi kawalan bagi sistem bampar hadapan aktif untuk mengurangkan kesan daya hentaman akibat perlanggaran. Metodologi kajian ini bermula dengan membangunkan model perlanggaran kenderaan 6 darjah kebebasan (DOF) berdasarkan pendekatan Kamal yang mewakili zon hancur kenderaan sebenar. Seterusnya, peredam MRE dwi-tindakan direka dan dimodelkan tingkah laku impaknya menggunakan polinomial darjah ke-4 untuk mengkaji ciri-ciri daya-anjakan. Pelantar ujian perlanggaran dibangunkan untuk menilai prestasi sistem bampar hadapan aktif dengan menjalankan eksperimen pada tahap perlanggaran yang berbeza termasuk ringan (83.25 kN), sederhana (333.02 kN) dan kuat (749.28 kN). Gabungan PID dan pengawal skyhook dilaksanakan dalam sistem bampar hadapan aktif. Kaedah yang dicadangkan telah mengurangkan kesan perlanggaran hadapan secara berkesan sebanyak 63.78%, 44.16% dan 30.06% dari segi pecutan. Manakala, anjakan dikurangkan sebanyak 55.56%, 37.54% dan 19.33% untuk hentaman ringan, sederhana dan keras.

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## APPROVAL

The Examination Committee has met on **27 February 2024** to conduct the final examination of **Amrina Rasyada Binti Zubir** on his degree thesis entitled **'Modified Kamal Model for Crumple Zone Behavior and Control of Active Front Bumper System for Head-On Collision'.**

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

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# APPROVAL

This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Science (Mechanical Engineering)**. The members of the Supervisory Committee were as follows.

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| | | |
|---|---|---|
| ABS | - | Anti-lock Braking System |
| ACO | - | Ant Colony Optimization |
| ADAMS | - | Automated Dynamic Analysis of Mechanical Systems |
| ADAS | - | Advanced Driver-Assistance Systems |
| AEB | - | Automatic Emergency Braking |
| ANFIS | - | Adaptive Neuro-Fuzzy Inference System |
| BPF | - | Band-Pass Filter |
| CIP | - | Carbonyl Iron Particles |
| DAQ | - | Data Acquisition |
| DOF | - | Degree-of-freedom |
| E&E | - | Elkady and Elmarakbi Model |
| EM | - | Exponential Model |
| ESC | - | Electronic Stability Control |
| FE | - | Finite Element |
| GA | - | Genetic Algorithm |
| GMT | - | Glass Mat Thermoplastic |
| GSA | - | Gravitational Search Algorithm |
| HGSPSO | - | Hybrid Gravitational Search Particle Swarm Optimization |
| HPF | - | High-Pass Filter |
| IPSO | - | Improved Particle Swarm Optimization |
| KM | - | Kamal Model |
| LB | - | Lower Boundary |

| | | |
|---|---|---|
| LPF | - | Low-Pass Filter |
| LVDT | - | Linear Variable Differential Transformer |
| MAE | - | Magneto-Active Elastomer |
| MKM | - | Modified Kamal Model |
| MR | - | Magneto-Rheological |
| MRE | - | Magnetorheological Elastomer |
| MREID | - | Magnetorheological Elastomer Isolator Device |
| PID | - | Proportional-Integral-Derivative |
| PIDF | - | Proportional-Integral-Derivative Filter |
| PM | - | Polynomial Model |
| POM | - | Polyoxymethylene |
| PSO | - | Particle Swarm Optimization |
| PWM | - | Pulse Width Modulation |
| R&D | - | Research and Development |
| RADAR | - | Radio Detection and Ranging |
| RCTD | - | Real Crash Test Data |
| RTV | - | Room Temperature Vulcanized |
| SLI | - | Speed Limit Information |
| SMC | - | Sheet Moulding Compound |
| UB | - | Upper Boundary |
| UPNM | - | Universiti Pertahanan Nasional Malaysia |
| USB | - | Universal Serial Bus |
| WHO | - | World Health Organization |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $\beta$ | - | Beta Parameter |
| $c$ | - | Damper Coefficient |
| $C_1$ | - | Skyhook Damper |
| $D$ | - | Number of Dimension |
| $F_{coll}$ | - | Collision Force |
| $F_d$ | - | Damping Force |
| $F_m$ | - | Force Model |
| $F_p$ | - | Force Prototype |
| $F_r$ | - | Froude Number |
| $g$ | - | Gravitational Acceleration |
| $G$ | - | Gravitational Constant |
| $k$ | - | Spring Constant |
| $K_d$ | - | Derivative Value |
| $K_i$ | - | Integral Value |
| $K_p$ | - | Proportional Value |
| $L$ | - | Length of Vehicle |
| $N$ | - | Number of Agent |
| $Q$ | - | Dissipative Energy |
| $T$ | - | Number of Iteration |
| $T$ | - | Kinetic Energy |
| $v$ | - | Velocity |
| $V$ | - | Potential Energy |

## LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

Conventional bumper design is less efficient in terms of total amount of energy absorbed during front collision because the front bumper is fix directly towards the vehicle body (NHTSA, 2018). They are designed to absorb and disperse energy upon impact but may not actively prevent or mitigate the force of a collision. Moreover, this bumper also unable to perform optimally in low-speed collisions, where the impact forces are minimal (Mo et al., 2018). As a result, this can lead to unnecessary damage to the vehicle.

As time goes by, the conventional vehicle bumper with passive systems that offer limited protection during collisions has evolved into an active front bumper system which made of two main components in the design namely, sensing system and a collapsible structure that extends from the front of the automobile to absorb impact energy where a more advanced system might be able to prevent or reduce damage (First-rate Mold Solution Co., Ltd., 2019).

In this study, an active front bumper system is developed using magnetorheological elastomer (MRE) dampers that is placed between the chassis and front bumper to reduce the effect of frontal collision which can causes crumple zone damage, unwanted acceleration and jerk or even worse fatalities. The main part of the damper is made of a smart material known as MRE that can change it stiffness and damping coefficient when induced with magnetic field.

To function as an effective system against the frontal impact, this study considers modelling the vehicle crash simulation that represents the arrangement of an actual vehicle crumple zone to carefully examine which part of the vehicle that affected during the accident. Furthermore, the impact behavior modelling of the MRE also takes place to identify the force-displacement characteristics when subjected to different stages of collision. Both validated models will be used to implement the suitable control strategy to evaluate the performance of the system.

The control strategy is developed based on the responses of displacement, acceleration, and transmitted force. Next, the collision test rig is developed and tested using a scaled vehicle. The experiment is conducted at different cases such as passive, active, and off state to evaluate the potential benefits of the active front bumper system in reducing the effect of frontal collision.

## 1.2 Problem Statement

Frontal collisions have been demonstrated to inflict more damage compared to rear collisions, primarily due to the concentration of crucial components such as the engine, transmission system, and radiator in the front of the vehicle (Florin Roebig, 2023). This high-density configuration of the crumple zone leads to less effective energy absorption and a greater transfer of force to the vehicle's structure, thereby contributing to passenger injuries, especially when the vehicle is traveling at higher speeds.

To mitigate these issues, various methods have been developed to minimize the impact of frontal collisions, including the integration of intelligent features into the vehicle's electronic systems, such as Automatic Emergency Braking (AEB) and Advanced Driver-Assistance Systems (ADAS). Utilizing sensors like RADAR and cameras, these systems provide real-time information to the driver and can take automatic actions based on the perceived obstacles (Vargas et al., 2021).

Additionally, an innovative approach involves the implementation of an active front bumper system incorporating magnetorheological elastomer (MRE) technology. This system aims to address the shortcomings of energy absorption in traditional bumper structures. By subjecting MRE samples to a magnetic field, the stiffness and damping properties are altered to enhance impact energy absorption. The front bumper is specifically designed to be sacrificed during frontal collision in order to absorb energy, thereby reducing the transfer of force to the occupant compartment, as illustrated in Figure 1.1 (Wang et al., 2021).

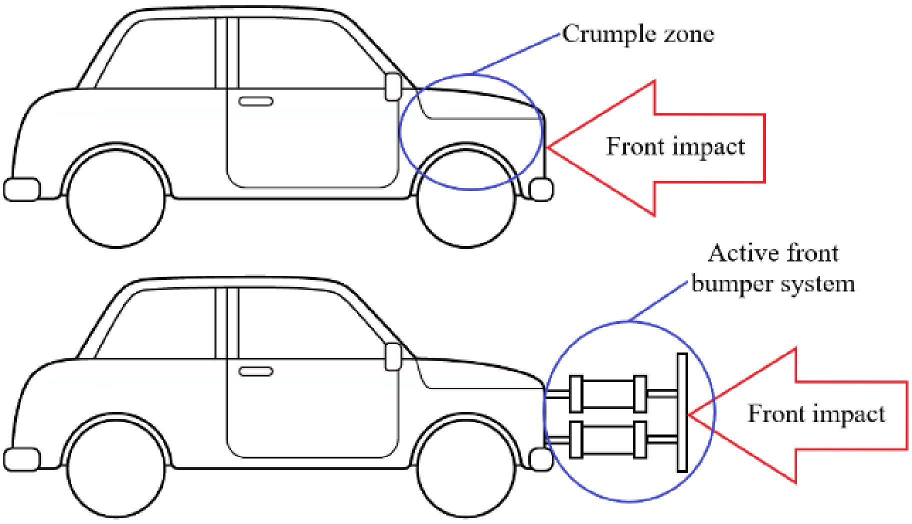


**Figure 1.1** Comparison between present bumper structure and active front bumper system

In order to ensure the effectiveness of the active front bumper system, creating a functional control structure according to the actual collision scenario has been a challenge throughout this study. This is to guarantee that the damper is capable of reducing the impact imposed on the vehicle body at different collision stages (light, medium and hard impact energies). Thus, before the experiment is carried out on the scaled vehicle, a vehicle crash model and a MRE model are initially simulated to obtain the accurate model parameters.

## 1.3 Research Objective

The aim of this study is to reduce the effect of frontal collision including the damage on the vehicle crumple zone, fatalities on the passenger, unwanted acceleration and jerk. The objectives of the research are:

(a) To model the dynamics of crumple zone during frontal collision using modified Kamal model.

(b) To model the impact behaviour of the dual-acting MRE damper in the form of force-displacement characteristics using a non-parametric polynomial approach.

(c) To develop a control strategy for active front bumper system that can reduce the effects of impact force due to collision.

### 1.4 Scope and Limitation of Study

The scope of this research focused on:

(a) Only frontal collision is considered in this study by neglecting the lateral impact and rear-end collision.

(b) Crumple zone modelling for frontal collision is develop based on Kamal model.

(c) Impact behavior modelling of MRE is based on force-displacement characteristics.

(d) The method used for controller and model optimization is gravitational search algorithm (GSA).

(e) The control strategy implemented in this study is developed by considering low computational cost with fast response.

(f) Experiment is conducted at low, medium and hard impact energies by varying the weight of pendulum.

(g) The results of the experiment is analyzed based on the displacement and acceleration responses.

However, there are several limitations that need to be overseen on this study such as:

(a) The characterization of the MRE is tested with the impact velocity of 2.24 m/s due to limitations of the drop impact test.

(b) The vehicle model is downscaled to 1:10 of the actual vehicle because of the high fabrication cost and limited space in the collision test rig.

(c) Modelling and control design are performed using Matlab-Simulink software.

(d) On-off current generator is applied in the inner loop of the controller for active front bumper system.

(e) Friction between the tire and road surface is neglected in both simulation and experiment.

### 1.5 Research Methodology

This research project started with the modelling of crumple zone based on Kamal model which has been modified into 6 degree-of-freedom vehicle crash model consists of six lumped masses, ten spring constants and four damper coefficients that represents the crucial parts of an actual vehicle. Each parameter are optimized using the gravitational search algorithm (GSA) until it closely follows the deformation and acceleration responses from the real crash test data (RCTD) obtained from TRL (1995) that is set as the benchmark of this project.

The project continues with the development of a dual-acting MRE damper which acts as an actuator in the active front bumper system. The damper is filled with solid and ring shaped MRE that are arranged along the body and wrapped with enameled copper coils where current is applied to produce magnetic field. A drop