Lecture Notes in Networks and Systems 960

Fausto Pedro García Márquez
Akhtar Jamil
Alaa Ali Hameed
Isaac Segovia Ramírez *Editors*

Emerging Trends and Applications in Artificial Intelligence

Selected papers from the International Conference on Emerging Trends and Applications in Artificial Intelligence (ICETAI)

Springer

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Editors

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Editors
Fausto Pedro García Márquez
Ingenium Research Group
University of Castilla-La Mancha
Ciudad Real, Spain

Alaa Ali Hameed
Department of Computer Engineering
Istinye University
Istanbul, Türkiye

Akhtar Jamil
National University of Computer
and Emerging Sciences
Islamabad, Pakistan

Isaac Segovia Ramírez
Ingenium Research Group
University of Castilla-La Mancha (UCLM)
Ciudad Real, Spain

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Preface

Emerging Trends and Applications in Artificial Intelligence

Selected papers from the International Conference on Emerging Trends and Applications in Artificial Intelligence (ICETAI)

This book is a compilation of the selected papers presented at the International Conference on Emerging Trends and Applications in Artificial Intelligence (ICETAI) in 2023.

The conference has been organized by the Istanbul Medipol University, Turkey, on September 08–09, 2023. This event brought together leading experts, researchers, scholars, and professionals from around the world to share their latest findings and explore the newest advances in the field of artificial intelligence. As technology continues to shape our lives, the role of artificial intelligence has become increasingly significant. This conference provided a unique opportunity to gain insights into the latest developments and applications of artificial intelligence in the digital age. From cutting-edge research to real-world applications, the conference provided a comprehensive overview of the field and its impact on society.

This conference managed a large number of submissions of original, high-quality research papers, where only a few were accepted. Authors submitted their work in areas related to artificial intelligence and its applications, including, but not limited to, machine learning, deep learning, computer vision, natural language processing, robotics, and more. All submissions were reviewed by a panel of experts in the field, and the accepted papers are presented in this book. This is an excellent opportunity for researchers, scholars, and professionals to showcase their work and contribute to the advancement of the field. Submissions were made through the conference website following the submission guidelines.

Each paper was peer-reviewed by at least two reviewers and evaluated based on originality, technical depth, correctness, relevance to conference, contributions, and readability. The papers were accepted based on technical merit, interest, applicability, and how well they fit a coherent and balanced technical program.

The conference was carried out in hybrid mode.

The book highlights some of the latest research advances and cutting-edge analysis of real-world case studies on computational intelligence, data analytics, IoT, and applications from a wide range of international contexts. It also identified business applications and the latest findings and innovations in Operations Management and the Decision Sciences, e.g.:

Data Analysis and Visualization

- Exploratory Data Analysis
- Statistical and mathematical modeling
- Business Intelligence

- Big Data Analysis
- Data Mining
- Cloud Computing Architecture and Systems
- ETL and Big Data Warehousing
- Business Intelligence
- Data Visualization
- Statistical Analysis

Computer Vision

- Document Analysis
- Biometrics and Pattern Recognition
- Remote Sensing & GIS
- Medical Image Processing
- Image and Video Retrieval
- Motion Analysis
- Structure from Motion
- Object Detection and Recognition
- Image Restoration
- Speech and Audio Processing
- Signal Processing

Artificial Intelligence

- Machine Learning
- Pattern Recognition
- Deep Learning
- Human–Computer Interactions
- Medical Image Processing
- Image and Video Retrieval
- Audio Video Processing
- Text Analytics
- Natural Language Processing
- Information Retrieval
- Robotics Applications

Internet of Things

- 3D Printing
- Securing IoT infrastructure
- Future of IoT and Big Data
- Internet of Things
- Intelligent Systems for IoT
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- Visual Analytics IoT
- Data Compression for IoT Devices
- IoT Services and Applications
- Education and Learning
- Social Networks Analysis

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- Software Evolution & Reuse
- Reverse Engineering
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- Data & AI Monetization and Products
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- Decision Support Systems

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About the Editors

Fausto Pedro Garcia Marquez Fausto works at UCLM as Full Professor (Accredited as Full Professor from 2013), Spain, Honorary Senior Research Fellow at Birmingham University, UK, Lecturer at the Postgraduate European Institute, Research Fellow at INTI International University & Colleges, Malaysia, and he has been Senior Manager in Accenture (2013-2014). He obtained his European PhD with maximum distinction. He has been distinguished with the prices: Runner Prize (2023), Nominate Prize (2022), Gran Maestre (2022), Grand Prize (2021), Runner Prize (2020) and Advancement Prize (2018), Runner (2015), Advancement (2013) and Silver (2012) by the International Society of Management Science and Engineering Management (ICMSEM), First International Business Ideas Competition 2017 Award (2017), etc. He has published more than 248 papers (156 JCR: 74-Q1; 42-Q2; 32-Q3; 8-Q4), some recognized as: "Progress in Photovoltaics: Research and Applications" (Q1, IF. 8.49, one of the most downloaded in first 12 months of publications, 2023), "Applied Energy" (Q1, IF 9.746, as "Best Paper 2020"), "Renewable Energy" (Q1, IF 8.001, as "Best Paper 2014"); "ICMSEM" (as "excellent"), "Int. J. of Automation and Computing" and "IMechE Part F: J. of Rail and Rapid Transit" (most downloaded), etc. He is the author and editor of over 50 books (Elsevier, Springer, Pearson, Mc-GrawHill, Intech, IGI, Marcombo, AlfaOmega,...), >100 international chapters, and 6 patents. He is the Editor of 5 Int. Journals, Committee Member more than 70 Int. Conferences. He has been Principal Investigator in 4 European Projects, 8 National Projects, and more than 150 projects for universities, companies, etc. His main interests are: artificial intelligence, maintenance, management, renewable energy, transport, advanced analytics, and data science.

He is being: Expert in the European Union in AI4People (EISMD), and ESF.; Director of www.ingeniumgroup.eu.; Senior Member at IEEE, 2021-... ; Honored Honorary Member of the Research Council of Indian Institute of Finance, 2021-... ; Committee Chair of The International

Society for management science and Engineering Management (ISMSEM), 2020-…. His main interests are: artificial intelligence, maintenance, management, renewable energy, transport, advanced analytics, data science.

Dr. Akhtar Jamil is Associate Professor in the Department of Computer Science at the National University of Computer and Emerging Sciences, Islamabad, Pakistan. Before joining FAST, he served as Assistant Professor and Vice Head of the Computer Engineering Department at Istanbul Sabahattin Zaim University, Istanbul, Turkey. He also served as a Lecture at COMSATS University, Islamabad. He has also worked in the industry as a developer for several years. He received his Ph.D. in machine learning and remote sensing from Yildiz Technical University, Istanbul, Turkey. He has published more than 50 high-quality papers in well-known journals and top conferences. He received a fully funded Ph.D. scholarship from the Turkish government. He is the founding member of the ICMI, ICAETA and ICCIDA conferences. He serves as a reviewer for several journals and conferences. He focuses on applied research for solving real-world problems. His current research interests include statistical machine learning, deep learning, pattern recognition, data analytics, image classification, and remote sensing.

Alaa Ali Hameed received his Master's degree in computer engineering from Eastern Mediterranean University, North Cyprus, in 2012, and his Ph.D. degree from the Department of Computer Engineering at Selcuk University, Turkey, in 2017. He worked as an Assistant Professor in the Department of Computer Engineering, at Istanbul Aydin University, Turkey, from 2017 to 2019. He then moved to Istanbul Sabahattin Zaim University, Turkey, where he worked as an Assistant Professor in the Department of Computer Engineering from 2019–2022. Currently, he is Assistant Professor in the Department of Computer Engineering at Istinye University, Turkey. He has published more than 60 technical articles in top international journals and conferences in a short span of time. He has served as a Program Chair and a Technical Program Chair member for many international conferences; also he has served as a Guest Editor for many SCIE journals. His research interests include digital signal and image processing, adaptive filters, adaptive computing, data mining, machine, and deep learning, big data and data analytics, neural networks and self-learning systems, and artificial intelligence.

Isaac Segovia Ramirez Industrial Engineer at ETSII of the University of Castilla-La Mancha, Ciudad Real (2015) and Master of Industrial Engineering at ETSII of the University of Castilla-La Mancha, Ciudad Real (2019). Associate professor of electronic courses in 2019–2020 in ETSII of the University of Castilla-La Mancha, Ciudad Real. Current PhD student, he is in collaboration with several national and European projects with the Department of Business Administration of the University of Castilla La Mancha and the (June 2013-present) Ingenium group. Winner of the international contest “Entrepreneurship 5+5” in Tunisia. He has been awarded with the “Advancement Prize for Management Science and Engineering Management with the Nominated Prize (2018)” for the article “Remotely Piloted Aircraft System and Engineering Management: A Real Case Study”. His main research interests are related to maintenance management, UAVs, renewable energy, detection of elements in surface by infrared radiation, etc.

Simultaneous Optimization of Ride Comfort and Energy Harvesting Through a Regenerative, Active Suspension System Using Genetic Algorithm

Hassan Sayyaadi(✉) and Jamal Seddighi

Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran
sayyaadi@sharif.edu, seddighi.sayyedjamal@mech.sharif.edu

Abstract. Active suspension systems have long been recognized as an effective means of improving ride comfort and vehicle handling. However, high energy consumption and a lack of economic justification have hindered their commercial adoption in the industry. In order to address the challenges, this research proposed an innovative control structure that utilizes linear electromagnetic actuators capable of functioning in both motor and generator modes. To implement the proposed method, a suitable vehicle dynamic model available within the Adams software was selected. An analytical model corresponding to the software model was then extracted and verified to ensure its accuracy and reliability for use in GA optimization algorithms. Assuming only ride maneuvers, a feedback control structure based on meaningful terms in vehicle dynamics was developed. Then by using a GA algorithm, the ride comfort and energy harvesting criteria were simultaneously optimized. Finally, by exploiting the most suitable set of coefficients in the developed control structure, the suspension system showed the ability to recover up to 650 watts of power on rough roads, while leading to a 45% improvement in ride comfort.

Keywords: Artificial Intelligence · Genetic Algorithm · Active Suspension · Ride Comfort · Energy Harvesting · Multi-objective Optimization

1 Introduction

Over the past three decades, active control technologies have been continually developed to enhance vehicle dynamics [1]. Among these technologies, active suspension systems (ASSs) have demonstrated significant potential in improving ride comfort and handling. Despite extensive research, challenges such as high costs, substantial energy consumption, and a lack of functional justification have hindered the practical application of ASSs in the automotive industry [2]. In passenger cars, suspension systems have the potential to harvest energy equivalent to 3% of fuel consumption [3]. In general, the design of any suspension system primarily focuses on achieving ride comfort and road holding [4]. In numerous previous studies, a weighted combination of multiple objectives has

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been optimized as a single fitness function [5]. In this research, linear electromagnetic actuators are used as active dampers. These actuators can function in both motor and generator modes. This research aims to optimize ride comfort and energy harvesting by utilizing a genetic algorithm.

1.1 Suspension System and Vehicle Vibration

In determining the damping behavior of a suspension, low damping results in a more comfortable ride but compromises the car's handling. The sky hook and ground hook methods are classical approaches in the control design of semi-active suspension systems. One primary limitation of these methods is that they only consider the vertical coordinates of an axle, neglecting other aspects of vehicle dynamics, which results in a deviation from reality. Another shortcoming is the lack of utilization of speed data and other information reflecting the dynamic state of the car [6]. Therefore, having access to vehicle speed data and an estimate of road quality can significantly enhance their performance [7]. Based on Fig. 1, in passive systems, the damping behavior of a suspension system is represented by a constant curve. In semi-active systems, the damping coefficient can be continuously adjusted within a wide range at any given moment [8]. In the second and fourth areas, the damping coefficient is negative, signifying energy production. An active suspension system is required for operation within these two areas [9].

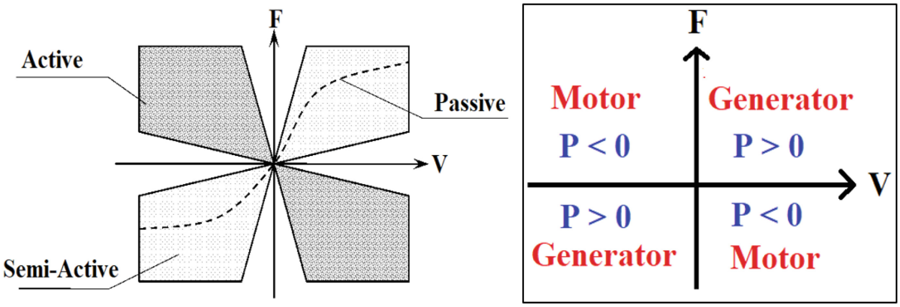

Fig. 1. Damping Behavior and Operational Scope of Renowned Suspension Control Systems

1.2 Ride Comfort Measurement

To evaluate a car's ride comfort, both subjective and objective methods are employed [10]. Various standards exist for the objective measurement of ride comfort [11]. The most prevalent among them is the ISO2631 standard [12]. According to this standard, the weighted mean square acceleration can be calculated using (1) in which $a_w(t)$ represents the weighted acceleration as a function of time, and T denotes the duration of data acquisition, expressed in seconds.

$$a_w = \left[\frac{1}{T}\int_0^T a_w(t)^2 dt\right]^{\frac{1}{2}} \tag{1}$$

1.3 Energy Harvesting Through Suspension System

The vibrations of a vehicle's suspension system have the potential to harvest part of the energy that would otherwise be wasted in the suspension's dampers [13]. The amount of harvested energy varies depending on factors such as vehicle speed, road quality, vehicle class, and the structure of the harvesting system [14]. Generally, the energy harvesting capacity of passenger car suspension systems is equivalent to 3% of the vehicle's fuel consumption, while off-road vehicles can achieve up to 6% [15]. Based on Fig. 1, in the second and fourth areas, negative power necessitates energy injection into the system. Conversely, in the first and third regions, the positive product of damping force and speed results in positive power, enabling energy harvesting [16]. To serve this purpose, an electromagnetic motor operating in both motor and generator mode can be used [17].

1.4 Optimization Using Genetic Algorithm

Optimization methods using Artificial Intelligence (AI) involve using algorithms and techniques to find the best possible solution to a complex problem. These methods are often used in industries such as logistics, manufacturing, and finance to improve efficiency and reduce costs [18]. There are several optimization methods that use AI, including Genetic Algorithms, Particle Swarm, and Ant Colony. These innovative approaches have been extensively utilized in the field of vehicle dynamics [19]. Genetic Algorithm is a type of optimization algorithm inspired by the process of natural selection in biological systems. It starts with a population of potential solutions to a problem, represented as "chromosomes" made up of genes. These chromosomes are evaluated for their fitness, or how well they solve the problem. The fittest chromosomes are then selected to "breed" and produce offspring, which inherit traits from their parents. This process of selection and reproduction continues for several generations, with the hope that the population will converge to a solution that is optimal or near-optimal [20].

Table 1. The vibrational characteristics of the studied

Parameter	Symbol	Unit	Front Axle Value	Rear Axle Value
Sprung Mass	m_s	kg	922	731
Unsprung Mass	m_u	kg	108	94
Axle Distance to Sprung CG	L_s	m	1.303	1.644
Tire Vertical Rate	K_t	N/m	420000	420000
Wheel Vertical Rate	K_w	N/m	105700	106200

2 Software and Analytical Modeling

In vehicle dynamics applications, Adams software offers results that closely resemble reality due to its precise modeling of geometry, kinematics, and dynamic properties of the chassis components [21]. To implement the method, a standard car model defined in

Adams software was utilized and illustrated in Fig. 2. The vibrational characteristics of the studied car are stated in Table 1.

2.1 Analytical Model Extraction

During the initial phase of designing a suspension vibration control system, it is crucial to develop a simplified model that closely resembles real-world conditions, can be easily coded, and incorporated into the optimization loop [22]. Hence, as depicted in Fig. 2, a four-degree-of-freedom model representing the vibrations observed from the side of the car was derived.

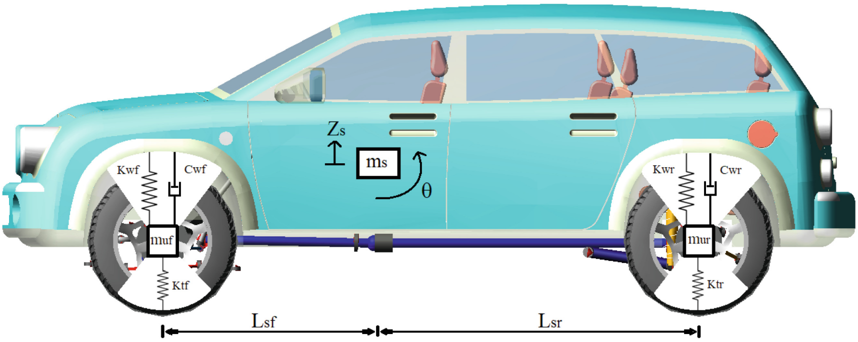

Fig. 2. Side-View Four Degree of Freedom Vibration Model of the Studied Vehicle

As represented in Eqs. 2 through 4, the undamped vibration equations of the analytical model have four generalized coordinates including z_s, θ, z_{uf}, and z_{ur} [23].

$$m_s\ddot{z}_s + K_{wf}\left(z_s - L_{sf}\theta - z_{uf}\right) + K_{wr}(z_s + L_{sr}\theta - z_{ur}) = 0 \tag{2}$$

$$I_s\ddot{\theta} + K_{wf}L_{sf}\left(z_s - L_{sf}\theta - z_{uf}\right) + K_{wr}L_{sr}(z_s + L_{sr}\theta - z_{ur}) = 0 \tag{3}$$

$$m_{uf}\ddot{z}_{uf} - K_{wf}\left(z_s - L_{sf}\theta - z_{uf}\right) - K_{tf}\left(z_{rf} - z_{uf}\right) = 0 \tag{4}$$

$$m_{ur}\ddot{z}_{ur} - K_{wr}(z_s + L_{sr}\theta - z_{ur}) - K_{tr}(z_{rr} - z_{ur}) = 0 \tag{5}$$

To verify the accuracy of the model, a straight-line bump test was conducted on the studied car using the Adams software. The same longitudinal speed and road bump input were then applied to the developed linear model. The results, which compare the vertical position of the front and rear axles of the sprung mass, are illustrated in Fig. 3. The simulation results of the linear half-car model exhibit coherence and similarity with the model developed in the Adams software.

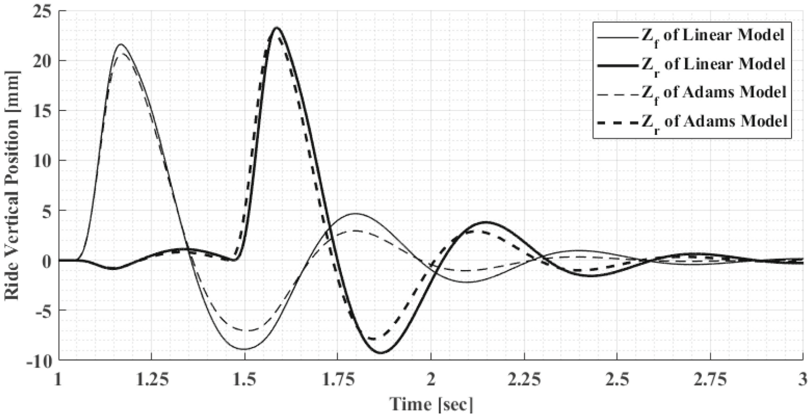

Fig. 3. Comparing Vertical Tip Positions of the Studied Vehicle for the Designed Bump Test

3 Defining the Control Structure and Parameters

Using Genetic Algorithm, this study aims to optimize ride comfort and energy harvesting. To achieve this, an optimal algorithm based on meaningful concepts in vehicle dynamics has been developed. In the 2DOF side-view vibration model, high-frequency vibrations of the unsprung mass can be disregarded, allowing the suspension and tire stiffness to be considered as an equivalent series stiffness.

3.1 Defining the Control Vector

The front and rear vertical forces can be expressed as follows:

$$F_f = F_f^{road} + F_f^u \tag{6}$$

$$F_r = F_r^{road} + F_r^u \tag{7}$$

The excitation force of the road and the suspension's actuator are as follows:

$$\begin{Bmatrix} F_f \\ F_r \end{Bmatrix}^{road} = \begin{bmatrix} K_f + C_f s & 0 \\ 0 & K_r + C_r s \end{bmatrix} \tag{8}$$

$$\begin{Bmatrix} F_z^u \\ F_\theta^u \end{Bmatrix} = \begin{bmatrix} 1 & 1 \\ -L_{sf} & L_{sr} \end{bmatrix} \begin{Bmatrix} F_f^u \\ F_r^u \end{Bmatrix} = \begin{Bmatrix} m_s^u \ddot{z}_s \\ I_s^u \ddot{\theta} \end{Bmatrix} \tag{9}$$

Therefore, the equation of the closed loop system is as follows:

$$\begin{aligned} &\begin{bmatrix} m_s + m_s^u & 0 \\ 0 & I_s + I_s^u \end{bmatrix} \begin{Bmatrix} \ddot{z}_s \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} C_f + C_r & C_r L_{sr} - C_f L_{sf} \\ C_r L_{sr} - C_f L_{sf} & C_r L_{sr}^2 + C_f L_{sf}^2 \end{bmatrix} \begin{Bmatrix} \dot{z}_s \\ \dot{\theta} \end{Bmatrix} + \\ &\begin{bmatrix} K_f + K_r & K_r L_{sr} - K_f L_{sf} \\ K_r L_{sr} - K_f L_{sf} & K_r L_{sr}^2 + K_f L_{sf}^2 \end{bmatrix} \begin{Bmatrix} z_s \\ \theta \end{Bmatrix} = \begin{bmatrix} 1 & 1 \\ -L_{sf} & L_{sr} \end{bmatrix} \begin{Bmatrix} F_f \\ F_r \end{Bmatrix}^{road} \end{aligned} \tag{10}$$

3.2 Defining the Control Parameters and Their Limitations

To establish the search space, the control coefficients are defined as follows:

$$-0.5 < \sigma_m^u = \frac{m_s^u}{m_s} < 1.5 \quad -0.5 < \sigma_I^u = \frac{I_s^u}{I_s} < 1.5 \tag{10}$$

$$0.1 < \zeta_f = \frac{C_f}{2\sqrt{\frac{m_s(1+\sigma_m^u)L_{sr}}{L}K_f}} < 0.7 \;\; 0.1 < \zeta_r = \frac{C_r}{2\sqrt{\frac{m_s(1+\sigma_m^u)L_{sf}}{L}K_r}} < 0.7 \tag{11}$$

4 Defining the Genetic Algorithm and the Test Procedure

Developing a control algorithm that can simultaneously optimize energy harvesting and ride comfort is the primary challenge of this research. The goal of a genetic algorithm is to find the best solution to this problem by mimicking the process of natural selection. The algorithm starts with a population of potential solutions, and then applies genetic operators such as mutation, crossover, and selection, to evolve the population towards better solutions [24].

4.1 Defining the Search Space and Initial Population

The search resolution was divided into 1024 parts using 10 house chromosomes, resulting in a binary matrix of 10 * 4 for each member of the population. A complete search of the search space would require over 1000 billion searches with this level of accuracy. However, genetic algorithms can efficiently find optimal points in less time by using targeted and intelligent search strategies [25].

$$N = \sum\nolimits_1^{10} a_n * 2^n \;\; N_{max} = 1024 \tag{12}$$

$$\sigma_{u,m} = -0.5 + \frac{N_{u,m}}{N_{max}} * 1.5 \, \zeta_{b,p} = 0.1 + \frac{N_{b,p}}{N_{max}} * 0.6 \tag{13}$$

4.2 Developing a Fitness Function for Evaluating Ride Comfort

To objectively assess the ride comfort for each pair of acceleration feedback coefficients, the frequency gains introduced in the ISO 2631 standard are utilized. The ride comfort criterion and the corresponding fitness function are then calculated as (15).

$$\begin{array}{r} \ddot{Z}_s^{\omega} = \ddot{Z}_s(\omega)W_k(\omega) \\ \ddot{\theta}^{\omega} = \ddot{\theta}(\omega)W_e(\omega) \end{array} \Rightarrow CFF = RMS\left(\sqrt{\left(\ddot{Z}_s^{\omega}\right)^2 + \left(\ddot{\theta}^{\omega}\right)^2}\right) \tag{14}$$

4.3 Developing a Fitness Function for Evaluating Energy Harvesting

To develop this fitness function, firstly, the feedback force required to control the acceleration of pitch and bounce modes is calculated. Then, using the coordinate transformation matrix, the force corresponding to the acceleration feedback in the front and rear axis is calculated.

$$\begin{aligned} F_b^u &= m_s^u \ddot{z}_s \\ F_p^u &= I_s^u \ddot{\theta} \end{aligned} \tag{15}$$

$$\begin{aligned} F_f^u &= 0.5579 F_b^u - 0.3393 F_p^u \\ F_r^u &= 0.4421 F_b^u + 0.3393 F_p^u \end{aligned} \tag{16}$$

Finally, by considering the damping force, the forces of the front and rear suspension actuator are calculated as follows:

$$\begin{aligned} F_f^d &= C_f\left(\dot{z}_s - L_f\dot{\theta} - \dot{z}_{uf}\right) \\ F_r^d &= C_r\left(\dot{z}_s + L_r\dot{\theta} - \dot{z}_{ur}\right) \end{aligned} \tag{17}$$

$$\begin{aligned} F_f^{act} &= F_f^u + F_f^d \\ F_f^{act} &= F_f^u + F_f^d \end{aligned} \tag{18}$$

After the suspension actuators' power is obtained as (20), by integrating the power, the suspension actuators' energy is computed as follows:

$$\begin{aligned} P_f^{act} &= F_f^{act} * \left(\dot{z}_s - L_f\dot{\theta} - \dot{z}_{uf}\right) \\ P_f^{act} &= F_f^{act} * \left(\dot{z}_s + L_r\dot{\theta} - \dot{z}_{ur}\right) \end{aligned} \tag{19}$$

$$\begin{aligned} E_f^{act} &= \int_t P_f^{act} dt \\ E_r^{act} &= \int_t P_r^{act} dt \end{aligned} \tag{20}$$

Therefore, the total harvested energy is calculated as follows:

$$EFF = E_f^{act} + E_r^{act} \tag{21}$$

4.4 Defining the Total Fitness Function

At this point, for each pair of acceleration feedback coefficient, the overall fitness function is defined as follows:

$$TFF = \left(\frac{\min(CFF)}{CFF} + \frac{EFF}{max(EFF)}\right)/2 \tag{22}$$

Table 2. Correlation between Vehicle Speed and Road Quality for Ride Test

Road Quality Based on ISO 8608	Vehicle Speed [km/h]
A	90, 100
B	70, 80
C	40, 50, 60
D	10, 20, 30

4.5 Designing the Test Procedure

The vertical dynamics of a vehicle's suspension system are primarily influenced by road's vertical geometry, necessitating a proper model for this application [26]. One precise and reliable technique for simulating a road profile involves using the power spectral density of the road profile in conjunction with inverse Fourier concepts [27]. Consequently, this research employs this method to reproduce the road profile. Based on ISO 8608, the power spectrum density of the road is used [28].

In reality, there exists a logical correlation between the road quality and the car's longitudinal speed [29]. As such, driving speeds on well-maintained roads tend to be higher than on poorly maintained ones [30]. While no standard and comprehensive relationship exists in this field, a review of previous related research has yielded appropriate and reasonable values, as presented in Table 2.

5 Optimization Process Execution and Result Comparison

This research focuses on improving ride comfort and energy harvesting during ride maneuvers. To achieve this goal, at various speeds, the corresponding roads are traversed by the studied vehicle.

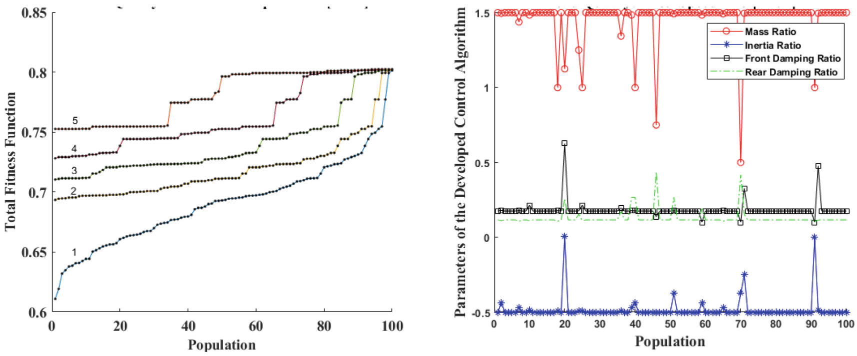

Fig. 4. The convergence of total fitness function at a speed of 25 km/h on a road with a quality rating of D, as well as the best selected individuals

5.1 Optimization Algorithm Convergence and The Best Selection

As a clarifying example, a ride test was conducted at a speed of 25 km/h on a road with a quality rating of D. The total fitness function was calculated and its convergence for first five iterations is depicted in Fig. 4, as well as the final population representing the best selected individuals.

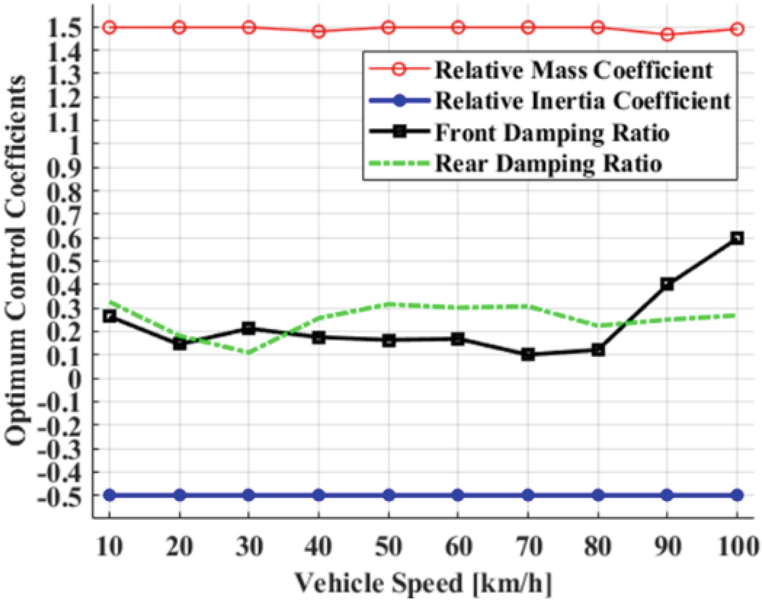

Fig. 5. Optimal control coefficients for various speeds

5.2 Performance Comparison Between Optimized and Base System

By utilizing the proposed control method and optimization algorithm, optimal control coefficients were determined for various speeds and illustrated in Fig. 5. To evaluate the efficacy of the optimized control system and compare its performance with that of the passive suspension system in the base car, a ride test was conducted on the studied vehicle over four different roads, each with varying levels of quality and corresponding speeds. The results, as presented in Table 3, demonstrate that the designed control system provides a 45% improvement in ride comfort.

The optimized control system not only enhances ride comfort but also exhibits significant power harvesting capabilities on rough roads. The study conducted in Table 3, reveals that both vehicle speed and road quality significantly impact the potential of the active suspension system to harvest power. Specifically, higher speeds and lower road quality lead to increased power harvesting potential. Beyond these factors, the policy or control logic of the suspension system also plays a critical role. In this research, the optimized control algorithm for each of the four suspension systems installed in the vehicle's corners has the potential to recover up to 650 watts of power on rough roads.

Table 3. Performance Comparison of the Optimized Control System and the Passive One

Parameter	Unit	Value			
Road Quality Based on ISO 8608	-	A	B	C	D
Vehicle Longitudinal Speed	km/h	100	75	50	25
Selected Mass Coefficient	-	1.5	1.5	1.5	1.5
Selected Inertia Coefficient	-	−0.5	−0.5	−0.5	−0.5
Selected Front Damping Ratio	-	0.6	0.11	0.16	0.18
Selected Rear Damping Ratio	-	0.27	0.25	0.32	0.14
Net Harvested Power	W	60	145	380	650
Comfort of Active System	-	0.23	0.33	0.55	0.67
Comfort of Passive System	-	0.35	0.59	0.99	1.49
Comfort Improvement	%	34	44	44	55

6 Conclusion

Active suspension systems face important challenges and shortcomings, such as high energy consumption, weight considerations, and a lack of economic justification. This research aims to address these imperfections and improve the performance of such systems. Specifically, the goal is to enhance ride comfort while also increasing energy harvesting capabilities. By doing so, this research seeks to contribute to the development of more efficient and effective vehicle suspension systems. In order to implement the method, firstly, a vehicle model available in Adams software was selected. For use in the optimization algorithm, an analytical model corresponding to the Adams model was extracted and validated. Based on meaningful concepts and parameters in vehicle dynamics, a logical search space was introduced, and finally, assuming driving maneuvers, a control structure was developed and optimized, using a genetic algorithm.

The method began by defining the search space, initial population, and fitness functions including ride comfort and energy harvesting. A wide range of ride tests were then conducted to implement the optimization algorithm, considering various road qualities and speeds. For each speed, the most appropriate set of control coefficients was selected. As a result, an optimized control was developed, which has a potential power recovery of up to 650 watts on rough roads. This optimized control leads to a 45% improvement in ride comfort. As a result, the study provides promising results for the development of more energy efficient and comfortable vehicles. In the subsequent stages of the study, the focus is on enhancing the yaw and roll stability of the vehicle in the handling maneuvers. To achieve this, an algorithm will be developed and optimized by considering the effect of the implemented actuators on the vehicle's yaw and roll dynamic behavior.