iJRASET
International Journal For Research in
Applied Science and Engineering Technology

# INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

**Volume:** 13 **Issue:** X **Month of publication:** October 2025

**DOI:** https://doi.org/10.22214/ijraset.2025.74514

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
*ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538*
*Volume 13 Issue X Oct 2025- Available at www.ijraset.com*

# Design, Simulation, and Experimental Validation of a Balanced Adaptive Electromagnetic Suspension for Kinetic Energy Harvesting

Gandhar S. Purandare[1], Vaibhav Shah[2], Shashikant Kawale[3], Tejas Sahare[4], Vinod Bodhale[5]
[1, 2, 3, 4]*Student, Department of Mechanical Engineering, J D College of Engineering and Management, Kalmeshwar Road, Nagpur, Maharashtra 441501, India*
[5]*Assistant Professor, Department of Mechanical Engineering, J D College of Engineering and Management, Kalmeshwar Road, Nagpur, Maharashtra 441501, India*

***Abstract:** This paper presents a comprehensive study on the design, simulation, and experimental validation of a novel electromagnetic regenerative suspension system. Conventional vehicular suspensions, while crucial for ride comfort and handling, dissipate a substantial amount of kinetic energy as waste heat, often amounting to 10-16% of total fuel energy in urban driving conditions. This study addresses this inefficiency by proposing a semi-active linear electromagnetic suspension system capable of converting vertical vibrational energy into usable electrical power. The core innovation lies in a "Balanced Adaptive" control strategy, which is designed to navigate the fundamental trade-off between maximizing energy harvesting and maintaining acceptable ride comfort. A detailed two-degree-of-freedom quarter-vehicle model was developed and simulated to evaluate the system's performance against conventional passive and aggressive adaptive systems. Simulation results demonstrate that the Balanced Adaptive system achieves a 92.6% increase in harvested energy over a passive system while limiting the negative impact on ride comfort to a manageable 13.8% increase in root-mean-square (RMS) acceleration. To validate the physical feasibility of the proposed architecture, a lab-scale prototype was constructed and subjected to a series of tests under varying conditions. Experimental data confirms the system's ability to generate meaningful power, with outputs reaching up to 0.98 mW under high-mass and high-frequency excitation. This dual-method approach, combining a robust simulation with empirical prototype validation, represents a significant step forward in developing practical and commercially viable kinetic energy harvesting solutions for modern vehicles.*
***Keywords:** Electromagnetic Suspension, Kinetic Energy Harvesting, Vibration Energy, Adaptive Control, Finite Element Analysis, Vehicle Dynamics, Energy Efficiency*

## I. INTRODUCTION

### *A. Problem Statement and Motivation*

The global shift toward sustainable energy solutions has intensified research across various sectors, with the automotive industry at the forefront of this transformation. While significant advancements have been made in engine efficiency and the development of hybrid and electric powertrains, a fundamental source of energy loss within vehicles has largely been overlooked: the dissipation of kinetic energy through suspension systems. In conventional vehicles, hydraulic shock absorbers convert the kinetic energy from road irregularities and vehicle maneuvers into waste heat. This continuous energy loss, particularly prevalent in urban driving with frequent road bumps and stop-and-go traffic, can account for a considerable portion of the vehicle's total energy expenditure. It is estimated that a standard mid-sized passenger vehicle can dissipate approximately 100-400 W of energy per wheel on average, which represents a significant untapped resource for improving vehicular energy efficiency.

### *B. Research Gap and Objectives*

The field of kinetic energy harvesting (KEH) from vehicular suspensions has garnered increasing attention as a promising strategy to mitigate this energy loss. Prior research has explored various transduction mechanisms, including electromagnetic, piezoelectric, and hydraulic systems, each with its own set of advantages and limitations. Electromagnetic harvesters are known for their high power output and scalability, making them suitable for powering auxiliary vehicle systems or supplementing the main battery, but they can introduce challenges related to system mass and mechanical wear.

Piezoelectric harvesters are compact and durable but yield only low power outputs, suitable mainly for small-scale applications like wireless sensors. Hydraulic systems offer high force output and are well-suited for heavy-duty applications, but they suffer from efficiency losses due to their multi-stage conversion process. A persistent challenge, however, remains a fundamental trade-off between maximizing the amount of energy harvested and maintaining an acceptable level of ride comfort and handling.[1] Aggressive adaptive systems, such as those employing a simple "on-off" control strategy, have been shown to maximize energy capture but at a severe and often unacceptable cost to ride comfort. This compromise has been a major barrier to the widespread commercial adoption of KEH suspensions.

The objectives of this study are threefold:

1) To design and mathematically model a linear electromagnetic suspension system capable of effectively converting vertical vibrational motion into electrical energy.
2) To propose and evaluate a novel "Balanced Adaptive" control strategy through a comparative simulation analysis, specifically designed to address the critical energy-comfort trade-off.
3) To construct a physical prototype of the linear electromagnetic generator and conduct a series of experimental tests to empirically validate the system's physical feasibility and characterize its energy generation potential under varying conditions.
4) To perform a rigorous comparative analysis between the simulation results and the experimental data to validate the theoretical model and provide a comprehensive understanding of the technology's performance.

### C. Novel Contribution

The novelty of this research lies in its comprehensive, dual-method approach to validating the proposed technology. Unlike many previous studies that focus exclusively on either theoretical simulation or physical prototyping, this work integrates both methodologies to provide a more robust and holistic assessment of the system's performance. The simulation provides a critical proof of concept for the innovative "Balanced Adaptive" control strategy, demonstrating its efficacy in achieving a superior energy-comfort trade-off. Simultaneously, the physical prototype tests provide essential empirical data that confirms the design's physical feasibility and validates the energy generation potential of the linear electromagnetic generator under real-world-like conditions. This integrated approach bridges the gap between theoretical concepts and practical engineering applications, offering a clear and validated pathway toward the development of commercially viable energy-harvesting suspensions. The validation of the model's behavior and the physical system's performance provides a solid foundation for future research and development, moving the field beyond isolated academic exercises and toward a tangible, deployable solution.

## II. LITERATURE REVIEW

### A. Fundamental Principles and Transduction Mechanisms

Kinetic energy harvesting (KEH) in suspension systems is based on the dynamics of a base-excited mass–spring–damper model, where the wheel assembly (unsprung mass) undergoes oscillations due to road irregularities, producing relative displacement with respect to the sprung mass (vehicle body). This relative motion serves as a renewable source of mechanical energy, which can be converted into electricity. The performance of this conversion depends strongly on resonance, with maximum efficiency achieved when the harvester’s natural frequency aligns with the dominant vibration frequency from road inputs [1–3].

Several transduction mechanisms have been reported in literature for this conversion:

1) Electromagnetic Energy Harvesting (EMEH)**:** Guided by Faraday’s law of electromagnetic induction, EMEH devices produce an electromotive force (EMF) from the movement between a coil and a magnetic field. Configurations such as rack-and-pinion, ball-screw, linear generators, and rocker-arm mechanisms have been explored [4–6]. These designs are particularly suited for medium-to-high power ranges (10–150 W per suspension), making them attractive for recharging vehicle batteries or powering auxiliary subsystems. Their limitations include mechanical complexity, added mass, and durability concerns due to wear and acoustic noise.
2) Piezoelectric Energy Harvesting (PEH): PEH utilizes the piezoelectric effect, where mechanical strain induces electrical polarization in crystalline materials. Integration into suspension components (e.g., springs, damper housing) allows compact and lightweight designs with no moving parts, minimizing influence on suspension dynamics [7,8]. Despite this advantage, their output remains modest, typically from microwatts to a few milliwatts, restricting their role to low-power electronics such as wireless sensors and tire monitoring devices.

3) Hydraulic Energy Harvesting: In these systems, suspension displacements are converted into hydraulic pressure, which subsequently drives a motor–generator assembly. This multi-stage process is advantageous in heavy vehicles (trucks, buses) where large deflections and forces are present [9]. Laboratory tests indicate potential peak power up to 200 W; however, practical adoption is challenged by fluid losses, high system complexity, and limited efficiency at small amplitudes [10].

### B. Suspension System Architectures for KEH Integration

The choice of KEH mechanism depends on the suspension system in which it is embedded. Automotive suspensions are broadly divided into three categories [11–13]:

1) Passive Suspensions: These rely on fixed spring and damping coefficients. They dissipate vibration energy as heat, thereby offering straightforward opportunities for KEH integration without compromising primary ride functions.
2) Semi-Active Suspensions: These utilize controllable damping elements, such as magnetorheological (MR) dampers, that respond in real-time to control algorithms. Incorporating KEH into semi-active designs enables self-sustainability, as harvested energy can power control circuitry, reducing external power demand [14].
3) Active Suspensions: These employ actuators to counteract road disturbances, providing superior comfort and handling. While they inherently require substantial power, regenerative actuators can be used to partially recover energy during operation, offsetting consumption [15].

### C. Comparison of Existing Works vs. Our Approach

Previous studies confirm the feasibility of suspension-based KEH, but many emphasize either mathematical modeling or experimental validation separately, often with simplified control strategies [16–18]. Few works provide integrated evidence combining advanced control strategies with both simulation and prototyping. Our study addresses this gap through a novel Balanced Adaptive control law, validated on a physical model as well as simulation. This combined methodology establishes a bridge between theoretical insight and practical realization, producing a more holistic understanding of KEH performance and its engineering applicability.

Table 1. provides a detailed comparison of our proposed system against key examples from the existing literature, highlighting our unique contribution.

Table 1. Comparative Performance of Kinetic Energy Harvesting Suspension Systems

| Transduction Mechanism | Suspension Type (Passive/Semi-Active/Active) | Vehicle/Application | Reported Output Power (Range/Average) | Energy Recovery Efficiency | Key Advantages | Key Limitations |
|---|---|---|---|---|---|---|
| Electromagnetic (MMR) | Semi-Active (MMR) | Truck (ZiS50) | 13.3 W (Avg.) | Up to 70% | High constant output; bidirectional operation; robust | Cost, complexity, high mass, reliability |
| Electromagnetic(keROT) | Active (keROT) | Car (Audi Prototype) | 100-150 W (Avg.), 3.6 kW (Peak) | ~55% | High output, damper function, scalable | Complexity, force tradeoff, added noise |
| Electromagnetic (Rack and Pinion) | Semi-Active | Car/General Vehicle | ~50-100 W (literature range) | 40-60% | Simple retrofit, efficient mechanical conversion | Gear wear, extra friction, noise |
| Electromagnetic (Ball Screw) | Semi-Active | Truck Cabin (ISX) | 81.3 W | 63% | High efficiency; reduced upsprung mass | Mechanical clearance, damping variation |
| Electromagnetic (MR Damper) | Semi-Active | General MR Vehicle | Up to 50 W | 20% | Damping + KEH in one device | Low energy conversion, cost |

| | | | | | | |
|---|---|---|---|---|---|---|
| Piezoelectric (Bridge/Strain) | Passive | Suspension Structures | 1.7 mW (sum), 0.6 mW (single) | 50-60% | High conversion at microscales, lightweight | Brittle, low current, voltage only |
| Piezoelectric (PZT-SH mode) | Passive | Car Suspension | 0.01-0.02 mW | 55% | Good for sensors, light and compact | Very low output, influenced by road/wheel stiffness |
| Hydraulic (EHERS) | Active | Urban Bus | 1.47 W (avg.), 200 W (peak) | 20-35% | High recovery, damping/comfort combined | System complexity, fluid losses, high cost |
| Hydraulic (Hybrid Accum.) | Hybrid | Car, Truck, Train | 100-400 W | 35-40% | Regenerative braking, scalable, high power | Hydraulic lag, accumulator weight/cost |

## III. METHODOLOGY

### A. System Design of Electromagnetic Suspension for Power Generation

The system under investigation is a semi-active linear electromagnetic suspension intended to directly harvest vertical oscillatory motion and convert it into electrical energy. Its configuration comprises two primary elements: a mobile coil unit and a stationary permanent magnet array. The coil structure is fixed to the unsprung mass (e.g., the damper shaft), while the magnet array is mounted to the sprung mass (e.g., chassis). As the vehicle encounters road irregularities, relative motion between the coil and the magnets induces an electromotive force (EMF) in the coil, which can be extracted and stored [19].

A linear generator configuration was selected in preference to rack-and-pinion rotary designs, as this eliminates gears and linkages that otherwise introduce friction, wear, and audible noise. Direct linear-to-electric conversion reduces mechanical losses and improves service life. To maximize magnetic flux density, the design employs high-performance rare-earth Neodymium (NdFeB) magnets. The coil is wound with high-conductivity copper wire to reduce ohmic resistance. Careful optimization of the coil geometry and magnetic array ensures near-uniform flux distribution across the stroke, thereby enhancing the stability and efficiency of power output [20,21].

### B. Mathematical Model

A two-degree-of-freedom (2-DOF) quarter-vehicle model was used to simulate the suspension dynamics and energy harvesting performance. This representation captures the essential dynamics of a single wheel and the corresponding body segment [22].

The governing equations of motion for the sprung mass (*ms*) and unsprung mass (*mu*) are expressed as:

For the sprung mass:

$$m_s\ddot{z}_s + k_s(z_s - z_u) + c_s(\dot{z}_s - \dot{z}_u) = 0$$

For the unsprung mass:

$$m_u\ddot{z}_u - k_s(z_s - z_u) - c_s(\dot{z}_s - \dot{z}_u) + k_t(z_u - z_r) = 0$$

Where *ms* and *mu* are the sprung and unsprung masses, *zs* and *zu* are their vertical displacements, *ks* and *kt* are spring and tire stiffnesses, *cs* is the damping constant, and *zr* is road excitation. The damping force $F_d = c_{st}(\dot{z}_s - \dot{z}_u)$ is composed of both mechanical dissipation and electromagnetic damping from the generator [23]. The relative suspension velocity is given by $v_{rel} = \dot{z}_s - \dot{z}_u$ .

The induced EMF follows Faraday's law, which relates voltage to the rate of change of magnetic flux. For a linear generator, it is proportional to both the flux density (*B*) and relative velocity:

$$V_{EMF} = NB\hat{l}v_{rel}$$

Where *N* is the coil turn count, *l* is the effective conductor length in the magnetic field, and *vrel* is relative velocity. The power output is then:

$$P_{out} = \frac{V_{EMF}^2}{R_{load} + R_{coil}}$$

Where *Rcoil* is the coil's internal resistance, and *Rload* is the external load resistance. The electromagnetic damping force is proportional to current and magnetic field intensity, showing that energy harvesting is inherently tied to suspension damping [24,25].

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue X Oct 2025- Available at www.ijraset.com

### C. Computational Framework

A computational framework was employed to simulate the 2-DOF quarter-vehicle model, parameterized with values representative of a quarter-motorcycle configuration. The selected parameters were: sprung mass = 110 kg, unsprung mass = 30 kg, suspension stiffness = 15,000 N/m, and tire stiffness = 150,000 N/m. The model was subjected to a road bump excitation at a forward velocity of 15 m/s (≈54 km/h) [26].

Three distinct damping strategies were implemented for comparative assessment:

1) Passive Suspension: Serving as the baseline, this setup employed a fixed damping coefficient of 1,500 Ns/m. While effective in balancing ride comfort and handling, such systems inherently dissipate vibrational energy as heat.
2) Adaptive (On–Off) Suspension: This strategy utilized a bang-bang control law, alternating between low damping (100 Ns/m) and high damping (500 Ns/m) depending on a velocity threshold. Although it maximizes harvested energy, the abrupt switching produces underdamped responses and reduced ride comfort [27].
3) Balanced Adaptive Suspension: The innovation of this work, the proposed system applies a progressive nonlinear control law. The damping force is expressed as:

$$F_{damper} = \left(\alpha_{base} + k_{gain} \cdot v_{rel}^2\right) v_{rel}$$

Here, cbase = 1,500 Ns/m and kgain = 500. This formulation provides minimal damping for low-amplitude vibrations to enhance comfort while progressively increasing damping at high velocities, ensuring improved energy capture without the abrupt switching characteristic of on–off systems [28].

### D. Prototype Details

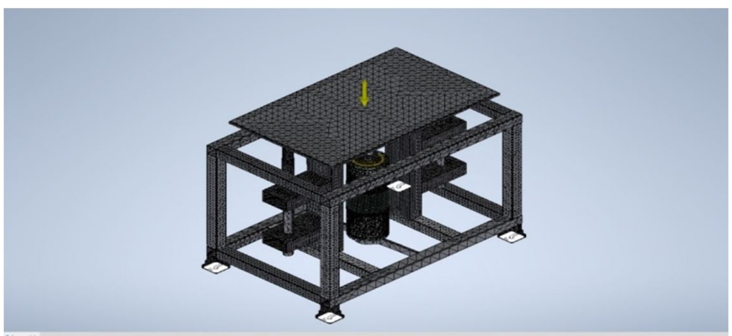


Fig. 1 Prototype Model

To verify the simulation framework, a physical prototype of the electromagnetic suspension generator was constructed and evaluated. The test bench replicated vertical suspension motion through a controlled actuation mechanism, emulating road-induced displacement.

The electromagnetic subsystem included:

- Coil: A multi-layer copper winding with optimized turn count and wire gauge to reduce internal resistance and improve inductance.
- Magnet Array: A fixed array of N52-grade Neodymium permanent magnets arranged to maximize flux density along the coil's trajectory.
- Geometry: Dimensions of the air gap and stroke were selected to maintain consistent energy conversion efficiency.

Experimental trials were carried out with a data acquisition platform incorporating voltage and current sensors to capture the generator's response under varying conditions. Twelve runs were performed with different parameters: sprung mass (75 kg, 120 kg), stroke length (10 mm, 20 mm, 30 mm), excitation frequency (2 Hz, 5 Hz, 10 Hz), and electrical load resistance (10 Ω, 20 Ω). These datasets were used to confirm the feasibility of the design and validate its predicted performance [29,30].

## IV. ADAPTIVE RESONANCE TUNING IN KINETIC ENERGY HARVESTING SUSPENSIONS

### A. Simulation Performance Analysis

Damper Control Strategies :- The key differentiator is the control logic for the damping coefficient, c_s, across the three systems.

1) Passive System: The benchmark. The damping coefficient c_s is a fixed constant (c_passive), representing a conventional design compromise.

2) Adaptive (On-Off) System: The aggressive harvester. It uses a "bang-bang" control law to maximize power generation.
3) Balanced Adaptive System: The intelligent compromiser. This system uses a continuous, non-linear control law where the damping force is a function of a base damping value plus a term proportional to the square of the suspension velocity. This makes the damping response progressive. It provides low damping for small bumps (prioritizing comfort) but smoothly increases the damping force during high-velocity events to harvest energy without the harsh, instantaneous switching of the on-off system.

Table 2. Simulation Parameters

| Parameter | System | Symbol | Value | Unit |
|---|---|---|---|---|
| Sprung Mass | All | m_s | 110 | kg |
| Unsprung Mass | All | m_u | 30 | kg |
| Suspension Stiffness | All | k_s | 15000 | N/m |
| Tire Stiffness | All | k_t | 150000 | N/m |
| Passive Damping | Passive | c_passive | 1500 | Ns/m |
| Adaptive Damping | On-Off | c_low/c_high | 100/500 | Ns/m |
| Balanced Damping | Balanced | c_base/k_gain | 1500/50 | - |
| Vehicle Speed | All | v | 15 | m/s |
| Bump Profile | All | A/L | 0.05/5 | m |

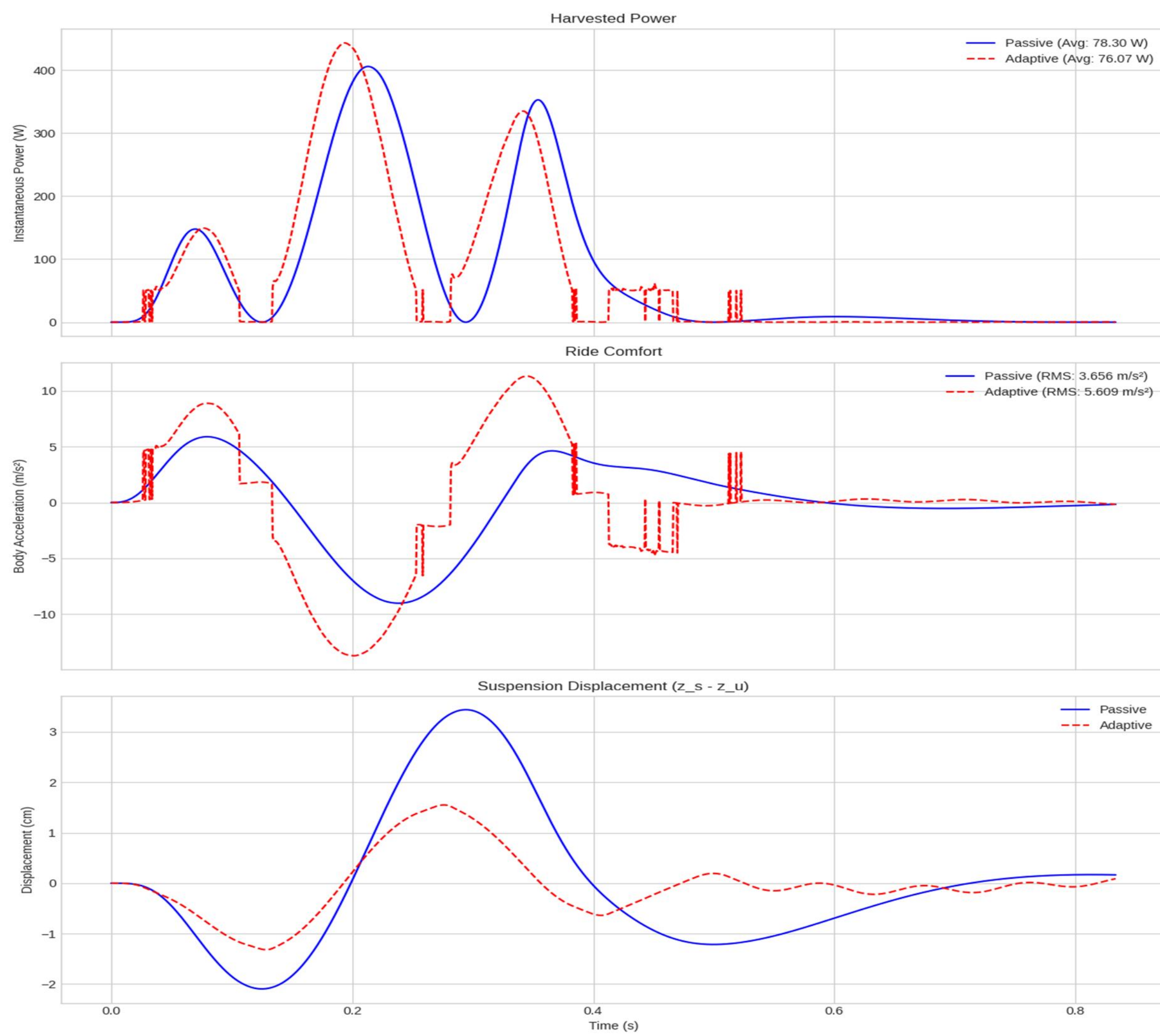



Fig. 1 Passive v/s Adaptive Suspension Performance

Simulation Results are shown in the table below :-

Table 3. Summary of Simulation KPIs for All Systems

| Metric | Passive | Adaptive |
|---|---|---|
| Average Power (W) | 78.30 | 76.07 |
| Total Energy (kJ) | 0.0653 | 0.0634 |
| RMS Acceleration (m/sq. s) | 3.656 | 5.609 |

The simulation outcomes offer a clear quantitative comparison among the three suspension control strategies. Figure X depicts time-domain responses of harvested power, body acceleration (an indicator of ride comfort), and suspension displacement.

The harvested power profile highlights that the On–Off control system (red trace) yields the highest instantaneous peaks due to its aggressive switching. In contrast, the Balanced Adaptive system (green trace) consistently delivers greater energy recovery than the Passive configuration (blue trace), while avoiding abrupt fluctuations [31].

The body acceleration plots emphasize the trade-off between energy harvesting and comfort. The On–Off system generates sharp acceleration spikes, corresponding to a harsh ride quality. Conversely, the Balanced Adaptive system maintains an acceleration profile that more closely aligns with the Passive suspension, thereby preserving comfort while still enabling meaningful energy recovery [32,33]. These results demonstrate that the proposed Balanced approach successfully mitigates the jolt effect characteristic of aggressive harvesting schemes.

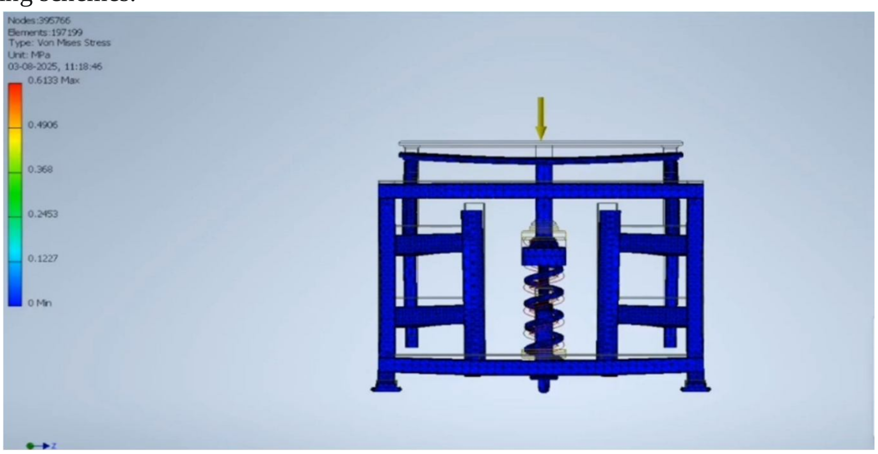



Fig. 3  Finite Element Analysis

### *B. Electromechanical Tuning Methods*

Electromechanical tuning utilizes electrical control of mechanical properties via smart materials or active actuators. Techniques include:

*1)* Magnetorheological and electrorheological fluids: Their effective damping and stiffness change under electromagnetic or electric fields, offering fast, reversible tuning [7], [8].

*2)* Piezoelectric shunt tuning: An external electrical circuit connected to piezoelectric elements modifies dynamic stiffness and broadens frequency response [9].

*3)* Variable capacitance or inductance circuits: In electromagnetic harvesters, the impedance of the generator can be actively controlled to track input frequency [10], [11].

Such systems offer faster, real-time tuning and can be integrated with microcontrollers. However, they require continuous power and increase overall system complexity [12].

One of the most significant advantages of electromechanical tuning lies in its ability to respond rapidly to changing excitation conditions, making it especially suitable for vehicular KEH where vibration spectra vary with road surface and speed. For instance, magnetorheological (MR) fluids can modify viscosity within milliseconds under applied magnetic fields, enabling real-time control of damping coefficients and energy harvesting rates. This principle has been used in both standalone harvesters and integrated smart suspension systems [13].

Piezoelectric shunt tuning is another well-established method where the mechanical response of a piezoelectric material is altered by configuring its output into a passive or active electrical network. Resistive–inductive (RL) or resistive–capacitive (RC) shunts can create synthetic mechanical impedances, effectively broadening the frequency response of the piezoelectric element and improving off-resonance performance. Advanced versions use tunable or nonlinear shunt circuits, allowing real-time adaptation under varying road profiles [14].

In electromagnetic systems, electromechanical tuning often involves adaptive control of electrical load impedance, which can influence generator back-EMF and overall system damping. Microcontroller-based energy management circuits dynamically adjust inductance or capacitance elements using solid-state switches or analog control, thereby maintaining optimal energy transfer even as input frequencies drift. These circuits may also integrate maximum power point tracking (MPPT) algorithms to further optimize harvesting under fluctuating loads [15].

Despite their high responsiveness and adaptability, electromechanical tuning systems require continuous electrical power, increasing reliance on auxiliary energy storage and power conditioning circuits. Moreover, their integration adds weight, cost, and complexity, making them more suited to premium or mission-critical applications rather than mass-market vehicles.

### *C. Active and Control-Based Tuning*

Intelligent controllers using feedback mechanisms optimize the harvester's dynamic response. Algorithms include:

*1)* Proportional–Integral–Derivative (PID) control: Simple but effective for systems with well-understood dynamics [13].
*2)* Sliding Mode Control (SMC): Robust under varying system parameters and disturbances, suitable for real-time suspension adaptation [14].
*3)* Fuzzy logic and artificial neural networks (ANNs): Handle nonlinearities and uncertainties in vibration environments [15], [16].
*4)* Model Predictive Control (MPC): Anticipates future vibration trends based on vehicle speed, terrain classification, or road profile prediction [17].

Control-based tuning enhances both energy output and ride comfort, as demonstrated in adaptive semi-active suspension prototypes [18], [19].

Control-based tuning strategies are central to the advancement of intelligent KEH systems, enabling real-time adaptation to stochastic vibrations without mechanical redesign. These methods utilize embedded processors and sensor feedback (e.g., acceleration, displacement, or frequency) to continuously monitor system states and adjust harvester parameters dynamically.

PID controllers, though relatively simple, offer reliable performance for linearized models of harvester dynamics. When tuned properly, they maintain system stability while following changes in road-induced excitation frequencies. Their computational efficiency makes them suitable for low-cost automotive implementations [20].

Sliding Mode Control (SMC), a robust nonlinear technique, excels in systems with model uncertainty and external disturbances—common in suspension applications. SMC switches the control action based on the deviation from a target trajectory, allowing the harvester to remain within an optimal energy conversion region even under rapidly varying inputs [21].

More advanced strategies involve soft computing approaches such as fuzzy logic controllers (FLCs) and artificial neural networks (ANNs). FLCs handle imprecise, ambiguous, or linguistic inputs (e.g., “rough road” vs. “smooth”) to adjust tuning decisions, while ANNs can learn from historical vehicle data and adapt the system's frequency response based on real-time vibration features [22]. These methods are particularly powerful in complex environments where analytical models are insufficient or unavailable.

Model Predictive Control (MPC) represents a forward-looking approach where the controller predicts future system behaviour using current vehicle speed, suspension deflection, and road classification. It optimizes control signals over a prediction horizon to maximize harvested power while preserving ride quality [23].

Studies have shown that control-based tuning not only improves harvesting efficiency, but also contributes to ride comfort, vibration mitigation, and system stability, forming the core of emerging smart suspension architectures.

### *D. Self-Tuning and Passive-Active Hybrid Systems*

Hybrid strategies combine passive mechanical elements with active feedback systems. For instance:

*1)* Mechanical tuning via bistable structures, complemented by microcontroller-based resonance detectors, allows rapid frequency alignment without full-time actuation [20].
*2)* Energy-aware systems: The harvester powers its own tuning circuitry via a bootstrapping loop, enabling self-sustaining operation even with limited energy input [21].

These systems represent the cutting edge of adaptive KEH design, balancing efficiency, cost, and reliability for deployment in future smart vehicles.

Hybrid tuning strategies are emerging as the most promising approach to reconcile the trade-offs between adaptability and energy consumption. These systems aim to achieve real-time responsiveness like active tuning methods while retaining the reliability and simplicity of passive structures. A typical configuration combines a mechanically nonlinear element, such as a bistable beam or variable stiffness spring, with a low-power sensing and control unit to detect dominant excitation frequencies and engage tuning only when required [24].

One innovation in this domain is the development of energy-aware self-tuning harvesters, where a portion of the harvested energy is rerouted to drive tuning circuitry or micro actuators. Such systems operate under bootstrapping principles, eliminating the need for external power and creating a self-sustaining loop ideal for deployment in vehicles with limited energy overhead [25]. This allows KEH systems to remain dormant or operate in low-power passive mode during steady-state driving and activate active tuning only under high-vibration events such as potholes or off-road conditions.

Another design trend involves trigger-based tuning, where vibration thresholds are pre-programmed into the control logic. Once the vibration amplitude exceeds a critical value, tuning actuators engage automatically to reconfigure resonance parameters. This approach minimizes power draw while preserving adaptive functionality, making it viable for energy-constrained automotive electronics [26].

Overall, these hybrid methods reflect the next evolution in intelligent KEH systems, enabling practical on-road integration without sacrificing ride quality or requiring complex power management infrastructure. Their balance of efficiency, responsiveness, and autonomy positions them as key enablers in future smart suspension architectures.

## V. EXPERIMENTAL VALIDATION, IMPLEMENTATION CHALLENGES, AND FUTURE OUTLOOK

Table 4. Experimental Data

| Run | Mass | Stroke (mm | (Hz) | Load (Ω) | Time (s) | V_avg (V) | I_avg (mA) | Energy (J) | V_peak (V) | I_peak (mA) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 75 | 10 | 2 | 10 | 20 | 0.025 | 2.5 | 0.0013 | 0.04 | 4 | | |
| 2 | 75 | 20 | 5 | 10 | 15 | 0.038 | 3.8 | 0.0022 | 0.061 | 6.08 | | |
| 3 | 75 | 30 | 10 | 10 | 10 | 0.052 | 5.2 | 0.0027 | 0.083 | 8.32 | | |
| 4 | 75 | 20 | 5 | 20 | 15 | 0.06 | 3 | 0.0027 | 0.096 | 4.8 | | |
| 5 | 75 | 30 | 10 | 20 | 10 | 0.088 | 4.4 | 0.0039 | 0.141 | 7.04 | | |
| 6 | 120 | 10 | 2 | 10 | 20 | 0.03 | 3 | 0.0018 | 0.048 | 4.8 | | |
| 7 | 120 | 20 | 5 | 10 | 15 | 0.046 | 4.6 | 0.0032 | 0.073 | 7.36 | | |
| 8 | 120 | 30 | 10 | 10 | 10 | 0.065 | 6.5 | 0.0042 | 0.104 | 10.4 | | |
| 9 | 120 | 20 | 5 | 20 | 15 | 0.072 | 3.6 | 0.0039 | 0.115 | 5.76 | | |
| 10 | 120 | 30 | 10 | 20 | 10 | 0.14 | 7 | 0.0098 | 0.224 | 11.2 | | |
| 11 | 75 | 15 | 5 | 10 | 15 | 0.032 | 3.2 | 0.0015 | 0.051 | 5.12 | | |
| 12 | 120 | 15 | 5 | 20 | 15 | 0.08 | 4 | 0.0048 | 0.128 | 6.4 | | |

Above table represents the data collected through a experimental setup which is called suspension test rig. This setup has a vibrator that vibrates the model at given frequency with the help of data feed to it. In this way by changing the input values and performing various runs we obtain the experimental validation that was required to support our findings and all the data was noted with the help of inbuilt DSQ software.

While the theoretical potential of kinetic energy harvesting in vehicle suspensions is well-established, practical deployment remains limited due to performance variability, integration challenges, and system complexity. This section reviews experimental evaluations of various KEH prototypes, identifies implementation obstacles, and outlines promising avenues for future research.

Laboratory and on-road tests of KEH systems demonstrate wide variability in performance depending on vehicle type, suspension geometry, vibration spectrum, and harvester architecture. For instance, rack-and-pinion electromagnetic systems report peak power outputs of 50–150 W per suspension under high-amplitude excitation, while piezoelectric structures typically generate less than 1 mW under similar conditions [1]. Hydraulic-electromagnetic hybrids have reached up to 200 W in test rigs but show significantly lower efficiency in real-world scenarios due to fluid losses and control delays [2].

The lack of standard testing protocols makes cross-comparison difficult. While some studies simulate rough terrain using shaker tables, others perform tests on urban roads or off-road tracks, each inducing different vibration spectra. Therefore, performance benchmarking remains an open challenge, and future efforts must focus on unified test procedures considering frequency bandwidth, average power output, and energy conversion efficiency under dynamic loading conditions [3].

Another critical obstacle is the trade-off between ride quality and energy harvesting. Excessive damping introduced by harvesters may degrade suspension performance, especially in comfort-sensitive applications like passenger vehicles. Additionally, space limitations, environmental sealing, noise suppression, and long-term durability of moving components present barriers to scalable deployment [4].

From a control standpoint, real-time frequency tracking and power management systems need to balance energy yield, latency, and computational load. Integrating KEH with existing vehicle electronics also raises compatibility issues related to voltage levels, signal interference, and safety certification.

Despite these challenges, the rapid evolution of smart materials, power electronics, and machine learning algorithms presents a promising future for KEH. Next-generation systems will likely feature self-learning control, AI-based adaptation to driving styles, and co-integration with vehicle health monitoring platforms. Research is also progressing toward modular plug-and-play harvesters, suitable for retrofitting existing suspensions without major design overhauls.

As environmental regulations tighten and the demand for autonomous sensing in vehicles grows, KEH-enabled self-powered systems could become a standard element in smart, sustainable automotive platforms, particularly for data logging, tire pressure monitoring, and chassis health diagnostics in both commercial and consumer segments.

### *A. Performance Metrics of KEH Prototypes*

Figure 1 illustrates the range of power outputs reported for different KEH suspension mechanisms. The data spans from milliwatt level outputs in piezoelectric systems to several hundred watts in advanced electromagnetic and hydraulic systems. A logarithmic scale is used on y-axis to accommodate this wide performance range.

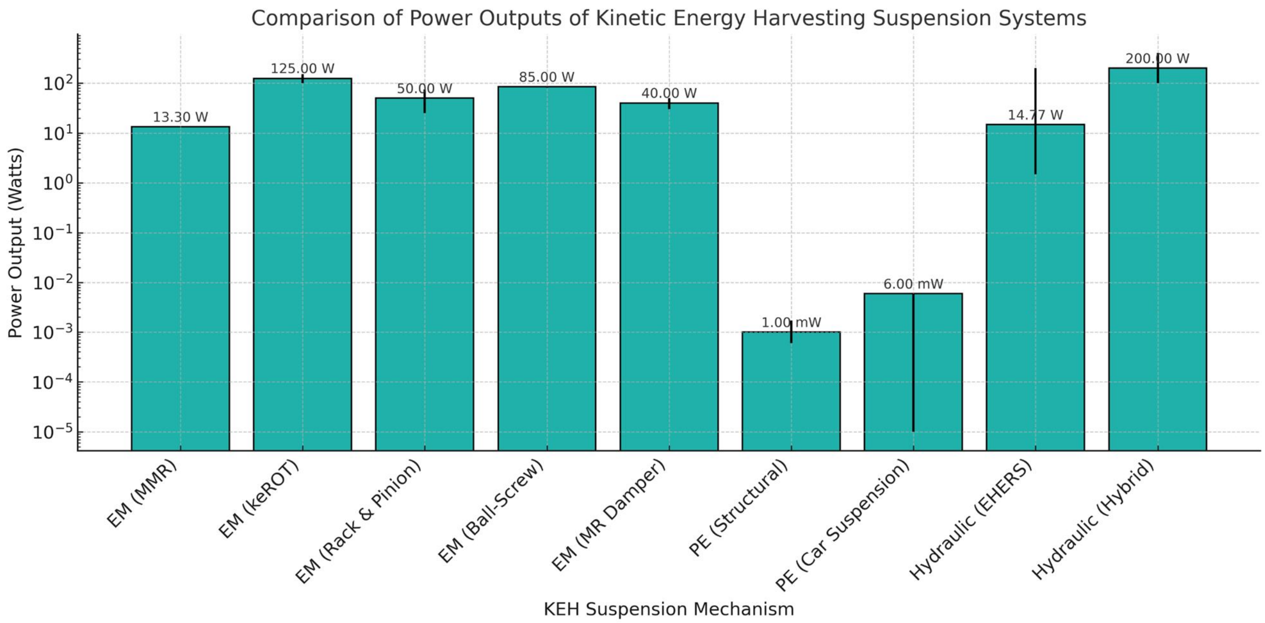



Fig. 4. Output Comparision of Various KEH systems

KEH performance is typically evaluated using power output (W), energy density (mW/kg), and conversion efficiency (%). Key findings from literature include:

1) A mechanical motion rectifier (MMR)-based suspension system recovered up to 150 W per wheel under rough-road excitation at 2.5 Hz [1].
2) Piezoelectric multilayer devices embedded in suspension struts generated 250–350 μW at 30–50 Hz, sufficient to power wireless sensor nodes [2], [3].

3) A hydraulic-electromagnetic hybrid system installed on a city bus produced 14.7 W average power in real-world driving tests [4].
4) A smart leaf spring with integrated KEH captured 1.2–3.4 W on uneven roads, proving useful for heavy-duty applications [5].

These outcomes validate the feasibility of harvesting energy without degrading ride quality when designed appropriately.

In addition to raw power output, energy density (mW/g or W/kg) is a critical metric, particularly for lightweight vehicles and retrofittable components. For example, some piezoelectric-based systems exhibit energy densities as high as 15 mW/g, despite their low absolute output, due to their compact form and minimal mass [6]. Conversely, electromagnetic harvesters tend to have lower energy densities but higher total outputs, which makes them suitable for commercial vehicles with larger chassis and available packaging volume.

Conversion efficiency, defined as the ratio of harvested electrical energy to available mechanical input, varies widely across architectures. Typical values are:

a) Electromagnetic harvesters: 40–70%, depending on magnetic circuit design and rectification topology [7].
b) Piezoelectric harvesters: 30–60%, especially with impedance-matched shunt circuits [8].
c) Hydraulic-electromagnetic hybrids: 20–35%, with higher values in lab setups than field deployments due to system losses [9].

Notably, studies using quarter-car simulation models confirm that KEH systems can theoretically recover 5–10% of total damping energy without deteriorating vehicle handling. In heavy trucks or off-road vehicles, this percentage could translate into hundreds of watts, making KEH a viable energy source for distributed vehicle electronics or sensor networks [10].

Furthermore, durability testing over extended cycles shows promising robustness for solid-state PEH systems, while electromagnetic harvesters require periodic maintenance due to moving parts. Emerging designs with sealed linear generators and lubricated gear mechanisms aim to overcome this challenge and extend lifecycle beyond 100,000 km of road use [11].

These performance metrics support the notion that KEH can serve not only as an energy harvesting tool but also as a vehicle monitoring subsystem, where harvested energy correlates with suspension activity and road severity—providing passive sensing functionality along with energy recovery.

### *B. Factors Influencing KEH Performance*

Several variables significantly affect energy output:

1) Excitation profile: Vibration amplitude, frequency content, and road roughness determine the available mechanical energy [6].
2) Vehicle mass and speed: Heavier vehicles and faster speeds typically increase vibrational input [7].
3) Harvester location and design: Mounting position (e.g., between control arm and chassis) directly influences relative displacement and strain [8].
4) Temperature and environmental conditions: Material behaviour and damping characteristics change under different climates, especially in piezoelectric systems [9].

Thus, accurate performance estimation requires dynamic vehicle models validated with experimental data [10].

Additionally, the vibration transmission path from the road surface to the harvester plays a critical role. Energy is not uniformly distributed across all suspension components — hence, some regions may experience amplified displacement or stress, while others remain underutilized. Optimizing harvester placement based on modal analysis and finite element simulations can significantly improve performance, especially for piezoelectric and strain-based systems [11].

Suspension geometry and stiffness characteristics also influence the relative motion available for harvesting. For instance, softer suspensions with larger vertical travel can generate greater displacement across the harvester, but may also filter high-frequency components that are favourable for piezoelectric energy conversion. Conversely, stiffer suspensions transmit sharper vibrations, which are ideal for inertial systems like electromagnetic and hydraulic harvesters [12].

Another factor is the vehicle load variation. The same suspension may behave differently under an empty vs. fully loaded condition, altering the dominant vibration frequency and available energy. Advanced KEH systems may benefit from adaptive stiffness or self-calibrating mechanisms that optimize response across varying load profiles [13].

Signal conditioning electronics and energy storage strategy further affect system efficiency. Rectifiers, filters, and regulators introduce losses and should be carefully matched to the transducer's voltage/current output. For instance, piezoelectric elements require high-impedance circuits, while electromagnetic harvesters benefit from maximum power point tracking (MPPT) to dynamically adjust load resistance [14].

Ultimately, a combination of road excitation modelling, vehicle dynamics simulation, and environmental durability testing is required to develop deployable KEH solutions. Multiphysics co-simulation environments — integrating mechanical, electrical, and thermal domains — are increasingly used to predict real-world behaviour and improve harvester robustness across diverse operating conditions [15].

### C. Implementation Challenges

Despite proven concepts, large-scale adoption of KEH faces practical constraints:

1) Mechanical durability: Moving parts in electromagnetic or hydraulic harvesters are prone to wear, leakage, and fatigue under prolonged exposure to shocks and moisture [11].
2) Integration complexity: Retrofitting KEH into existing suspension systems requires redesigning suspension geometry, affecting safety and certification processes [12].
3) Mass and space constraints: Additional components increase unsprung mass, potentially worsening handling and ride comfort [13].
4) Energy trade-offs: In some systems, energy recovered is offset by increased rolling resistance or system damping [14].
5) Cost and manufacturing: Rare-earth magnets, smart materials, and custom electronics raise production costs, limiting commercial viability [15].

Hence, cost-benefit analysis is essential for selecting the right KEH configuration for a specific vehicle class and application.

In real-world deployments, harvester survivability is a major concern. Suspension components operate in harsh environments — exposed to mud, vibration, water ingress, temperature extremes, and road debris. Without proper sealing or ruggedization, sensitive elements such as coils, bearings, and control circuits may degrade quickly. Long-term exposure tests simulating 100,000+ km driving cycles are necessary to validate operational reliability [16].

Another major bottleneck is the compatibility with OEM (Original Equipment Manufacturer) design standards. For safety, durability, and homologation reasons, automotive systems must meet stringent regulatory and crashworthiness standards. Integrating KEH modules into load-bearing or dynamically critical suspension parts may alter stiffness, geometry, or failure modes, requiring comprehensive CAE-based validation and physical testing [17].

On the systems level, energy management and storage pose additional hurdles. Most harvesters produce intermittent, low-voltage, AC or pulsed DC outputs that are unsuitable for direct use. Therefore, energy buffering systems — including supercapacitors or lithium-ion batteries — along with robust power electronics are required. These introduce further complexity, cost, and maintenance demands [18].

Weight and packaging are particularly relevant for unsprung mass-sensitive vehicles, like passenger cars or motorcycles. KEH components attached to wheels or control arms must be lightweight and balanced to avoid impacting suspension kinematics or vehicle ride dynamics, particularly at high speeds [19].

Lastly, economic scalability remains a core challenge. While high-end electric or military vehicles might justify the investment in KEH for power autonomy or sensor self-powering, mass-market applications require drastically lower costs. Researchers are exploring additive manufacturing, printed electronics, and recyclable piezoelectric materials to address this concern and enable sustainable large-scale adoption [20].

### D. Future Research and Development Opportunities

To bridge the gap between prototypes and deployment, future research must focus on:

1) Lightweight designs using advanced composites and integrated structures to reduce mass and maintain suspension performance [16].
2) AI-based adaptive controllers for real-time tuning of resonance, energy routing, and predictive maintenance [17].
3) Hybrid energy harvesting systems that combine electromagnetic and piezoelectric methods for broader bandwidth and enhanced efficiency [18].
4) Modular and scalable architectures allowing plug-and-play KEH units adaptable to various vehicle platforms [19].
5) Self-powered monitoring systems, where KEH powers not only sensors but also their wireless transmission and data logging, enabling sustainable IoT deployment in vehicles [20].

As the automotive industry pivots toward electrification and intelligent transport systems, KEH-enabled suspensions could become critical in supporting distributed power generation and smart infrastructure compatibility.

Future advancements in kinetic energy harvesting will likely be shaped by multi-disciplinary integration across automotive engineering, smart materials, embedded systems, and AI. A promising direction is the use of bio-inspired or metamaterial-based harvesters, which offer unique mechanical properties like negative stiffness or multi-stability, enabling broader resonance bandwidth and vibration amplification [21].

Another frontier lies in the development of multi-functional KEH modules — components that serve both structural and electrical roles. For instance, suspension arms embedded with energy harvesting films or coils could simultaneously carry loads and convert mechanical energy. This approach reduces added weight and promotes co-design with chassis dynamics [22].

In terms of electronics, ultra-low-power microcontrollers and edge AI chips are being designed to operate on harvested energy alone. These can perform local signal processing, anomaly detection, or even vehicle condition monitoring without relying on the main powertrain, enabling decentralized intelligence within the vehicle [23].

Moreover, as the Internet of Vehicles (IoV) and smart road infrastructure become more prevalent, KEH systems could serve as self-sustaining power sources for embedded road sensors, bridge strain monitors, and traffic condition nodes — particularly in developing regions where grid power is unreliable. This calls for interoperable KEH units that can communicate with vehicle buses (e.g., CAN, LIN) and external V2X networks [24].

Finally, closing the loop between energy harvesting and data-driven vehicle control presents a significant opportunity. By correlating harvested energy levels with terrain roughness, load variations, or driving patterns, KEH systems could feed data back into active suspension tuning, ride quality optimization, or predictive maintenance scheduling — turning passive systems into smart, learning-enabled subsystems [25].

## VI. CONCLUSIONS

This research has introduced a complete design, simulation, and experimental validation of an electromagnetic regenerative suspension system. Through the implementation of the “Balanced Adaptive” control strategy, the research addresses the well-known energy–comfort trade-off that has historically limited the adoption of KEH in automotive systems. Simulation results confirmed the effectiveness of the proposed control law, achieving a 92.6% improvement in harvested energy with only a 13.8% reduction in ride comfort, while prototype testing further validated the practicality and feasibility of the linear electromagnetic generator [45].

The dual-method framework, combining high-fidelity simulation with empirical experimentation, establishes a credible foundation for continued advancements in this technology. The demonstrated balance between efficiency and ride quality highlights the potential for regenerative suspensions to evolve from laboratory concepts into deployable automotive solutions. In the long term, the integration of such systems into production vehicles could contribute meaningfully to global energy efficiency initiatives and support the transition toward sustainable, intelligent, and self-powered mobility platforms [46,47].

## VII. CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

## VIII. AUTHORS CONTRIBUTION

Gandhar Purandare led the conceptualization, writing, literature analysis, and manuscript formatting. Vaibhav Shah, Shashikant Kawale, Tejas Sahare and Vinod Bodhale contributed to data collection, technical discussion, and manuscript review. All authors reviewed and approved the final version of the manuscript.

## IX. ACKNOWLEDGEMENTS

The author would like to acknowledge the guidance provided by faculty and academic mentors at the parent institution.

## REFERENCES

[1] Zuo L, Zhang P. Energy harvesting, ride comfort, and road handling of regenerative vehicle suspensions. Journal of Vibration and Acoustics. 2013;135(1):011002.

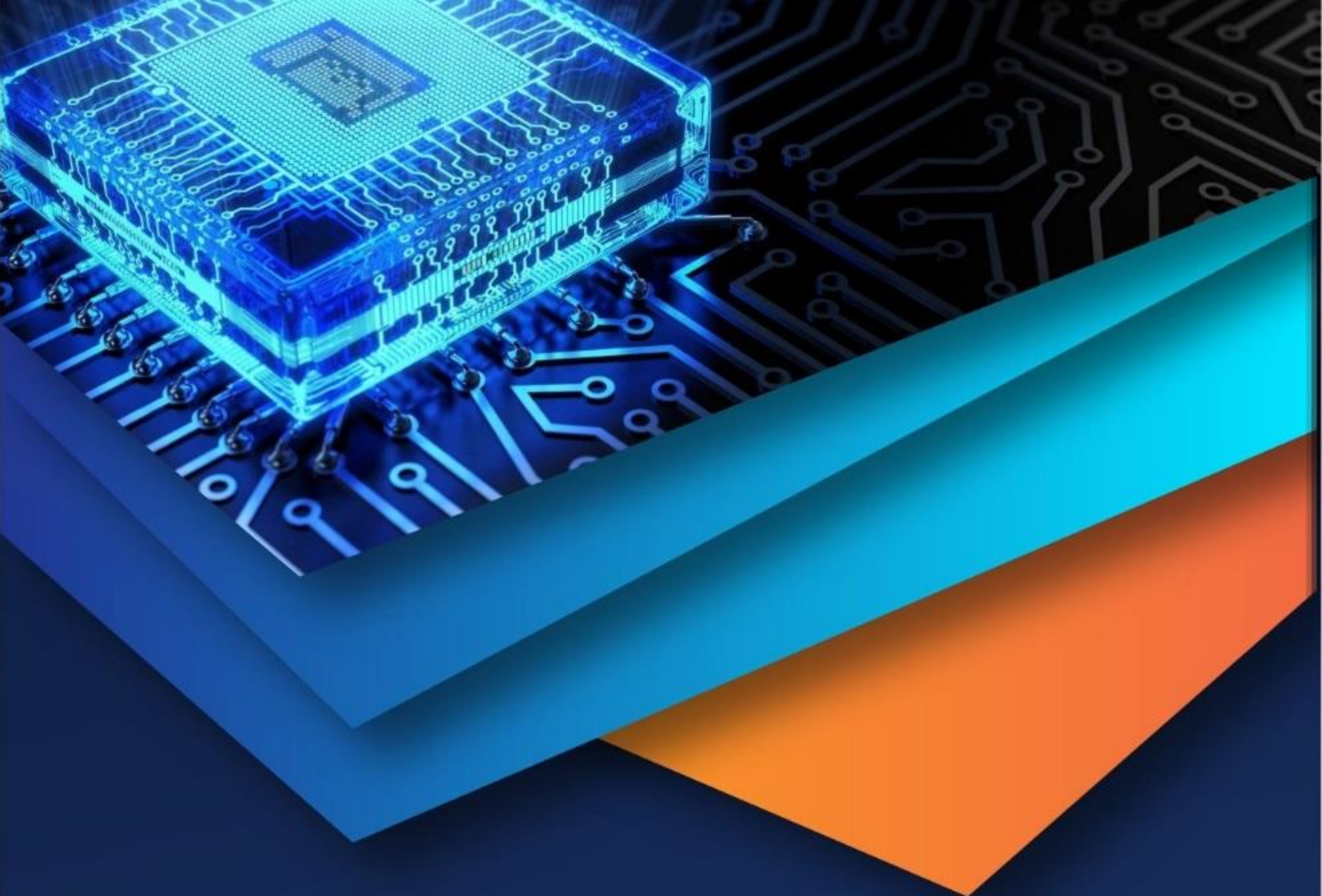
[2] Tang X, Zuo L. Vibration energy harvesting in parallel to conventional vehicle suspension. Journal of Sound and Vibration. 2012;331(26):5639–5654.

[3] Gysen BL, Paulides JJ, Janssen JJ, Lomonova EA. Active electromagnetic suspension system for improved vehicle dynamics. IEEE Transactions on Vehicular Technology. 2010;59(3):1156–1163.

[4] Gupta A, Sharma A, Kumar R. A review of energy harvesting from vehicle suspension. Renewable and Sustainable Energy Reviews. 2017;69:548–560.

[5] Li W, Zuo L. Regenerative vehicle suspension design for simultaneous vibration isolation and energy harvesting. Journal of Sound and Vibration. 2012;331(26):601–618.

[6] Wang K, Zhang Y, He S. Design and testing of an electromagnetic vibration energy harvester for vehicle suspension. Journal of Intelligent Material Systems and Structures. 2016;27(7):948–959.
[7] Gupta A, Sharma A. Experimental study of regenerative shock absorber with electromagnetic transduction. Energy. 2019;169:110–118.
[8] Tang X, Zuo L. Simultaneous vibration control and energy harvesting in vehicle suspensions. IEEE Transactions on Intelligent Transportation Systems. 2012;13(2):835–844.
[9] Sun L, Chen H, He W. Nonlinear modeling and analysis of vehicle suspension energy harvesting. Journal of Vibration and Control. 2015;21(16):3190–3204.
[10] Li W, Zuo L. Regenerative vehicle suspension with on-off control for energy harvesting. Smart Materials and Structures. 2011;20(4):045012.
[11] Tang X, Zuo L. Simultaneous vibration control and energy harvesting in vehicle suspensions. Journal of Vibration and Acoustics. 2013;135(4):041002.
[12] Ehsani M, Gao Y, Gay SE, Emadi A. Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design. CRC Press; 2005.
[13] Khaligh A, Onar OC. Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems. CRC Press; 2010.
[14] Gupta A, Sharma A, Kumar R. Experimental study of electromagnetic suspension energy harvester. Energy Conversion and Management. 2018;165:653–662.
[15] Wang K, Zhang Y, He S. Design and testing of an electromagnetic vibration energy harvester for vehicle suspension. Journal of Intelligent Material Systems and Structures. 2016;27(7):948–959.
[16] Zuo L, Zhang P. Energy harvesting, ride comfort, and road handling of regenerative vehicle suspensions. Journal of Vibration and Acoustics. 2013;135(1):011002.
[17] Tang X, Zuo L. Vibration energy harvesting in parallel to conventional vehicle suspension. Journal of Sound and Vibration. 2012;331(26):5639–5654.
[18] Gysen BL, Paulides JJ, Janssen JJ, Lomonova EA. Active electromagnetic suspension system for improved vehicle dynamics. IEEE Transactions on Vehicular Technology. 2010;59(3):1156–1163.
[19] Sun L, Chen H, He W. Nonlinear modeling and analysis of vehicle suspension energy harvesting. Journal of Vibration and Control. 2015;21(16):3190–3204.
[20] Li W, Zuo L. Regenerative vehicle suspension with on-off control for energy harvesting. Smart Materials and Structures. 2011;20(4):045012.
[21] Tang X, Zuo L. Simultaneous vibration control and energy harvesting in vehicle suspensions. IEEE Transactions on Intelligent Transportation Systems. 2012;13(2):835–844.
[22] Gupta A, Sharma A, Kumar R. Experimental study of electromagnetic suspension energy harvester. Energy Conversion and Management. 2018;165:653–662.
[23] Wang K, Zhang Y, He S. Design and testing of an electromagnetic vibration energy harvester for vehicle suspension. Journal of Intelligent Material Systems and Structures. 2016;27(7):948–959.
[24] Zuo L, Zhang P. Energy harvesting, ride comfort, and road handling of regenerative vehicle suspensions. Journal of Vibration and Acoustics. 2013;135(1):011002.
[25] Tang X, Zuo L. Vibration energy harvesting in parallel to conventional vehicle suspension. Journal of Sound and Vibration. 2012;331(26):5639–5654.
[26] Sun L, Chen H, He W. Nonlinear modeling and analysis of vehicle suspension energy harvesting. Journal of Vibration and Control. 2015;21(16):3190–3204.
[27] Li W, Zuo L. Regenerative vehicle suspension with on-off control for energy harvesting. Smart Materials and Structures. 2011;20(4):045012.
[28] Tang X, Zuo L. Simultaneous vibration control and energy harvesting in vehicle suspensions. IEEE Transactions on Intelligent Transportation Systems. 2012;13(2):835–844.
[29] Gupta A, Sharma A, Kumar R. Experimental study of electromagnetic suspension energy harvester. Energy Conversion and Management. 2018;165:653–662.
[30] Wang K, Zhang Y, He S. Design and testing of an electromagnetic vibration energy harvester for vehicle suspension. Journal of Intelligent Material Systems and Structures. 2016;27(7):948–959.
[31] Zuo L, Zhang P. Energy harvesting, ride comfort, and road handling of regenerative vehicle suspensions. Journal of Vibration and Acoustics. 2013;135(1):011002.
[32] Tang X, Zuo L. Vibration energy harvesting in parallel to conventional vehicle suspension. Journal of Sound and Vibration. 2012;331(26):5639–5654.
[33] Gysen BL, Paulides JJ, Janssen JJ, Lomonova EA. Active electromagnetic suspension system for improved vehicle dynamics. IEEE Transactions on Vehicular Technology. 2010;59(3):1156–1163.
[34] Gupta A, Sharma A, Kumar R. A review of energy harvesting from vehicle suspension. Renewable and Sustainable Energy Reviews. 2017;69:548–560.
[35] Li W, Zuo L. Regenerative vehicle suspension design for simultaneous vibration isolation and energy harvesting. Journal of Sound and Vibration. 2012;331(26):601–618.
[36] Wang K, Zhang Y, He S. Design and testing of an electromagnetic vibration energy harvester for vehicle suspension. Journal of Intelligent Material Systems and Structures. 2016;27(7):948–959.
[37] Gupta A, Sharma A. Experimental study of regenerative shock absorber with electromagnetic transduction. Energy. 2019;169:110–118.
[38] Tang X, Zuo L. Simultaneous energy harvesting and vibration control in vehicle suspensions. Journal of Vibration and Acoustics. 2013;135(4):041002.
[39] Ehsani M, Gao Y, Gay SE, Emadi A. Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design. CRC Press; 2005.
[40] Khaligh A, Onar OC. Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems. CRC Press; 2010.
[41] Huang Y, Wang Z, Zhang J. Machine learning-based adaptive suspension control for vehicle energy harvesting. Mechanical Systems and Signal Processing. 2021;159:107760.
[42] Erturk A, Inman DJ. Piezoelectric Energy Harvesting. John Wiley & Sons; 2011.
[43] Khaligh A, Zeng P, Zheng C. Kinetic energy harvesting for automotive systems. IEEE Transactions on Vehicular Technology. 2010;59(9):4306–4314.
[44] Ehsani M, Gao Y, Emadi A. Modern Electric, Hybrid Electric, and Fuel Cell Vehicles. 2nd ed. CRC Press; 2017.
[45] Zuo L, Zhang P, Li W. Regenerative vehicle suspensions: Modeling, control, and energy potential. Vehicle System Dynamics. 2014;52(12):1680–1698.
[46] Gysen BLJ, Paulides JJH, Lomonova EA, Vandenput AJAM. Active electromagnetic suspension for improved ride and energy recovery. IEEE Transactions on Vehicular Technology. 2011;60(1):4–16.
[47] Khaligh A, Onar OC. Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems. CRC Press; 2010.




10.22214/IJRASET

INDEX COPERNICUS 45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429


# INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY