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Review of Kinetic Energy Harvesting via Adaptive Suspension Resonance

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

***Abstract:** This review explores kinetic energy harvesting via adaptive suspension resonance in vehicles, focusing on the conversion of vibrational energy into usable electrical power. It addresses the inefficiencies in traditional suspension systems and examines various energy harvesting mechanisms including electromagnetic, piezoelectric, and hydraulic transduction methods. The paper highlights the importance of adaptive resonance tuning to match varying road-induced vibration frequencies and discusses control strategies such as classical, modern, and intelligent systems. Challenges in practical implementation, such as mechanical complexity, retrofitting issues, and trade-offs between comfort and energy recovery, are also analysed. A comprehensive review of recent prototypes and their performance metrics is presented, emphasizing the potential of these technologies to contribute to vehicle electrification, fuel efficiency, and intelligent system integration. This review also highlights the comparative advantages and trade-offs among transduction methods across various suspension types. By addressing both theoretical principles and real-world limitations, it bridges the gap between concept and application. Emerging trends in hybrid systems and AI-based control strategies are discussed to guide future research directions.*

***Keywords:** Kinetic energy harvesting, Adaptive suspension, Vibration energy, Electromagnetic, Piezoelectric, Vehicle efficiency*

I. INTRODUCTION

The increasing urgency of global energy sustainability and the tightening of automotive emission standards have intensified research into alternative energy solutions. A notable area gaining momentum is kinetic energy harvesting (KEH) from vehicular suspension systems. Despite advances in engine efficiency and hybrid-electric drivetrains, approximately 10%–16% of total fuel energy is still dissipated as waste through traditional suspension damping, especially in urban driving conditions where stop-and-go traffic is frequent [1], [2].

Conventional suspension systems employ hydraulic shock absorbers designed to dampen vibrations and improve ride comfort. However, these systems inevitably convert mechanical vibration into heat, leading to a continuous loss of usable energy [3]. This dissipated energy—originating from road irregularities and dynamic vehicle maneuvers—represents a significant, yet underutilized, source of mechanical energy that can potentially be harvested [4], [5].

Kinetic energy harvesting from suspension systems provides a consistent and ambient source of power, in contrast to intermittent systems like regenerative braking. By capturing the vertical oscillations of the suspension, KEH systems can generate electrical power to drive low-power onboard systems such as wireless sensors, lighting, or semi-active control mechanisms, thus reducing the load on the vehicle's alternator and improving fuel economy [6], [7].

Moreover, integrating KEH aligns with broader automotive trends, including electrification, smart sensor networks, and vehicle weight reduction. These systems can simplify electrical wiring through wireless solutions and support autonomous diagnostics via self-powered sensor modules, contributing to more efficient and intelligent vehicles [8], [9].

Nevertheless, the efficiency of KEH is fundamentally influenced by frequency matching between the ambient excitation and the harvester's natural frequency. Vehicle-induced vibrations are highly variable, governed by engine speed, vehicle type, terrain, and suspension geometry [10]. Fixed-frequency harvesters often operate far from resonance under these dynamic conditions, resulting in diminished output power [11].

This challenge has led to the emergence of adaptive resonance mechanisms in suspension energy harvesters. These systems dynamically adjust their structural parameters to align the resonance frequency with the changing excitation profile. Techniques include mechanical tuning, variable stiffness materials, and intelligent control algorithms [12], [13]. Such adaptive systems aim to maintain high conversion efficiency across diverse operational scenarios and vehicle types.

Ultimately, the evolution from traditional shock absorbers to intelligent, energy-harvesting suspension modules signifies a fundamental shift in vehicular energy management. This approach not only targets enhanced energy utilization but also supports the development of autonomous and self-powered subsystems, paving the way for next-generation sustainable vehicles [14], [15].

In conventional automotive systems, a substantial amount of kinetic energy generated during motion, road undulations, and braking is dissipated as heat via hydraulic or passive dampers. This inefficiency, often overlooked, can represent up to 10–15% of total vehicle energy losses, particularly in off-road or urban driving conditions [3], [8]. Recovering this energy through kinetic energy harvesting (KEH) techniques has thus become a promising strategy for enhancing overall vehicular energy efficiency.

KEH systems are particularly attractive for electric and hybrid vehicles, where harvested suspension energy can supplement onboard power requirements, reduce battery load, and extend driving range [4]. These systems offer dual functionality: maintaining suspension performance while simultaneously converting vibrational energy into electrical output. Unlike regenerative braking—which only operates during deceleration—suspension-based KEH works continuously as long as the vehicle is in motion, making it a more consistent and potentially scalable energy recovery solution.

Recent developments in materials science, low-power electronics, and embedded sensors have made the integration of KEH into automotive suspension systems increasingly feasible. Combined with modern vehicle control systems, KEH-enabled suspensions could form a core part of future intelligent energy management platforms [2], [9]. Additionally, as governments and manufacturers push for more energy-efficient transportation, such technologies could play a critical role in meeting sustainability benchmarks and reducing CO_2 emissions from road transport.

The next sections of this paper provide a systematic review of the working principles, recent advancements, comparative performance, and practical challenges associated with the application of KEH technologies in vehicle suspension systems.

II. FUNDAMENTAL PRINCIPLES AND TRANSDUCTION MECHANISMS FOR KINETIC ENERGY HARVESTING

Energy harvesting from suspension systems requires a combination of efficient vibration capture and robust mechanical-to-electrical conversion methods. Various transduction techniques have been developed to enable this, each suited to different vehicle dynamics, frequency ranges, and power requirements. In typical road conditions, a moving vehicle is subjected to continuous dynamic excitations due to uneven road surfaces, acceleration/deceleration forces, and load transfers during turning or braking. These excitations cause the suspension to oscillate in the vertical direction, which provides a consistent source of mechanical energy. Capturing this vibrational energy requires the harvester to be tuned to the dominant frequency band of vehicle suspensions, generally between 1–25 Hz depending on the road profile and vehicle type [10], [11].

The theoretical basis for energy extraction lies in modelling the suspension and harvester system as a base-excited mass-spring-damper system. The relative motion between the vehicle chassis and wheel assembly can be harnessed using linear or rotary transducers that convert kinetic energy into electrical energy through electromagnetic, piezoelectric, or hydraulic means. Each transduction mechanism exhibits unique characteristics in terms of power output, frequency response, and mechanical integration.

Furthermore, the challenge lies not only in maximizing harvested energy but in ensuring that the harvester does not negatively affect the suspension's primary function—passenger comfort and vehicle handling. A well-designed energy harvesting suspension should therefore strike a balance between energy recovery and dynamic response performance.

The following subsections explore the major transduction methods employed in KEH suspensions, providing an overview of their operational principles, design implications, and practical limitations.

A. Principles of Vibration-Based Energy Harvesting

Most KEH systems function as inertial spring-mass-damper systems. These devices consist of a proof mass suspended by a spring within a housing that experiences vibrations. When the base vibrates, the mass moves relative to the housing, producing mechanical strain or displacement that can be harvested using an appropriate transducer [1].

A critical design condition is resonance. When the system's natural frequency matches the dominant frequency of ambient vibrations, energy transfer is maximized, particularly in systems with high Q-factors [2]. However, in real-world vehicle operations, vibration frequencies are not fixed—they fluctuate based on speed, terrain, payload, and suspension geometry. Thus, fixed-frequency harvesters often fail to maintain optimal energy output [3], [4].

To overcome this, researchers have developed broadband and adaptive resonance techniques such as frequency tracking, nonlinear stiffening, and multi-modal structures [5], [6]. These methods are increasingly relevant as suspension-induced vibrations span from a few Hz in city traffic to over 100 Hz on rough highways [7].

In vehicle applications, most KEH devices operate under base excitation — where the housing of the energy harvester experiences motion due to road-induced vibrations, and a proof mass moves relative to this housing. The extent of relative displacement, and hence energy conversion, depends on the interplay between inertia, damping, and system stiffness. These factors collectively determine the amplitude response of the harvester and its ability to track dynamic inputs.

One of the major obstacles in suspension-based energy harvesting is that vehicle vibrations are often broadband and irregular, especially in real-world driving scenarios. Sudden braking, potholes, speed bumps, and varying payloads lead to constantly shifting excitation frequencies. Traditional harvesters designed for a fixed resonance condition often underperform under these circumstances.

To mitigate this, recent studies have explored adaptive tuning methods. These include variable stiffness components, magnetic levitation-based nonlinearities, and smart damping techniques that can adjust system parameters on-the-fly. Other promising approaches involve multi-modal harvesters, which are engineered to respond to more than one frequency band, thus improving energy capture over varying terrains.

Ultimately, effective KEH in vehicle suspensions must accommodate the non-stationary nature of the vibrational input. Designing harvesters that are not only efficient at resonance but also adaptable to changing excitation profiles remains a central challenge in this domain [8], [9], [10].

B. Electromagnetic Energy Harvesting (EMEH)

Electromagnetic harvesters operate on Faraday's law: relative motion between a conductor (coil) and a magnetic field induces an electromotive force (EMF), driving a current through a load [8].

Key EMEH architectures include:

- Rack-and-pinion systems: Convert vertical suspension motion into rotational movement to drive a generator [9].
- Ball-screw systems: Offer high-efficiency linear-to-rotary motion conversion with minimal backlash [10].
- Linear generators: Directly translate linear suspension oscillations into voltage using rare-earth magnets and coils [11].
- Rocker-arm systems: Used in Audi's eROT, they convert wheel motion into rotary energy via a lever arm [12].
- Mechanical Motion Rectifiers (MMRs): Convert bidirectional shock absorber motion into unidirectional generator input, increasing consistency and durability [13].

EMEH systems typically provide higher power output and are suitable for larger energy demands. However, challenges include increased system mass, component wear, and acoustic noise due to moving mechanical parts [14], [15]. Advanced designs now incorporate rare-earth magnets and magnetic circuits to enhance output while minimizing losses [16].

Among all KEH mechanisms, EMEH systems are often considered the most scalable due to their ability to generate relatively high-power levels, typically in the range of 10–150 W per suspension unit depending on the design and vehicle speed [17]. Their fundamental advantage lies in the direct conversion of kinetic energy into electrical power without requiring intermediate fluidic or structural transformations. This makes them highly suitable for powering auxiliary vehicle systems, sensors, or even contributing to the main battery in hybrid and electric vehicles.

Mechanical-to-electrical efficiency in EMEH designs is strongly influenced by magnetic flux density, coil geometry, and the speed of relative motion between components. To maximize energy recovery during normal suspension travel, many systems now employ neodymium-based rare-earth magnets and multi-layer copper coils to increase voltage output and reduce internal resistance losses [18]. Additionally, optimized magnetic circuit designs, such as Halbach arrays, are being integrated to focus magnetic fields and improve generator compactness.

However, the inclusion of mechanical gear interfaces — such as rack-and-pinion or ball-screw mechanisms — introduces mechanical noise, frictional losses, and wear over time. This raises durability concerns for long-term use in automotive environments. To address this, some research groups have shifted towards MMR-based linear generators, which use one-way clutches and flywheels to standardize rotary motion and reduce oscillatory reversal stress on the generator shaft [19].

One emerging trend in EMEH design is the use of modular harvesters mounted near each wheel, enabling distributed energy recovery and simplifying maintenance. These modular systems can be tuned individually for specific road conditions or axle loads, further enhancing system-level output and efficiency.

C. Piezoelectric Energy Harvesting (PEH)

PEH devices exploit the piezoelectric effect, where mechanical stress on materials like lead zirconate titanate (PZT) or polyvinylidene fluoride (PVDF) induces surface charges [17]. These materials are often integrated into vehicle components such as leaf springs, suspension arms, or damper bodies [18].

Multilayer configurations can significantly increase power output by increasing the active surface area and enhancing electric field coupling [19]. Compression and bending modes are commonly used to induce stress, while impedance matching ensures optimal energy transfer to the external circuit [20].

Though highly compact and energy-dense, PEH systems generate low current outputs, making them ideal for low-power applications like tire pressure monitors or wireless sensor nodes [21]. Their key advantages lie in their lack of moving parts, long service life, and easy integration into existing suspension components.

In vehicle suspension environments, piezoelectric harvesters are typically implemented using cantilever beams, stack actuators, or embedded layers in structural elements that experience cyclical deformation. Compression-mode configurations, such as those placed within dampers or bushings, convert axial loads from suspension compression into electrical output. Alternatively, bending-mode designs — often implemented on arms or brackets — utilize vehicle pitch and roll to drive flexural motion in the piezo layer [22].

One notable advantage of PEH systems is their lack of complex mechanical parts, which results in silent operation, reduced wear, and minimal interference with suspension dynamics. Additionally, their low-profile design allows seamless embedding in locations where electromagnetic or hydraulic harvesters may not be feasible due to space constraints or mechanical incompatibilities.

However, the power output of PEH systems remains in the range of microwatts to a few milliwatts, which restricts their use to energy-autonomous microdevices rather than large-scale energy recovery. Research is ongoing into the use of composite materials, such as carbon-fibre-reinforced PZT matrices, and frequency up-conversion mechanisms that can bridge the mismatch between suspension excitation frequencies and piezoelectric resonance bands [23].

For sensor-rich platforms like connected vehicles or intelligent tires, piezoelectric harvesters can provide local, maintenance-free energy for accelerometers, strain gauges, and wireless transceivers. Their durability, light weight, and high voltage-to-mass ratio make them well-suited for distributed sensor networks within modern vehicular systems [24].

D. Hydraulic Energy Harvesting

Hydraulic energy harvesters convert the linear reciprocating motion of the suspension into fluid pressure, which then drives a hydraulic motor coupled with a generator [22]. These systems are often implemented using piston pumps, double-acting cylinders, and check valves to convert bidirectional movement into unidirectional fluid flow [23].

Hydraulic-electromagnetic hybrid systems have shown promising results in prototypes, including:

- Electro-hydraulic energy-regenerative suspension (EHERS) for buses, recovering up to 14.77 W in real-world operation [24].
- Lab-scale systems achieving up to 200 W under ideal excitation [25].

Advantages include high force output, robust energy absorption, and thermal management. However, their multi-stage conversion path (mechanical → fluid → electrical) introduces efficiency losses, and issues like leakage, added system mass, and slow response at low amplitudes remain challenging [26].

Hydraulic systems are particularly attractive for heavy-duty applications such as trucks, buses, and rail systems, where large suspension displacements and high forces are prevalent. Their ability to handle high loads and harsh environments makes them suitable for both energy harvesting and damping simultaneously. In typical setups, the suspension compression drives a hydraulic piston, which pumps fluid into an accumulator or through a turbine generator, producing electricity as fluid pressure is released [27].

One key advantage of hydraulic systems lies in their force amplification capability. Because fluids are nearly incompressible, even small suspension motions can generate significant pressure differentials. This allows efficient energy transfer from low-frequency oscillations — common in vehicle suspensions — into rotational energy suitable for electricity generation.

Furthermore, hybrid configurations that integrate hydraulic actuators with electromagnetic generators can improve overall system response and controllability. These systems can be tuned to offer variable damping profiles depending on terrain and speed, enhancing vehicle ride comfort while also harvesting energy [28]. For example, prototype hybrid EHERS systems in urban buses have shown real-time adaptive damping while recovering meaningful energy in stop-and-go conditions.

Despite their potential, hydraulic KEH systems face engineering and integration challenges.

These include the need for high-performance sealing to prevent leakage, added system weight from accumulators and fluid reservoirs, and reduced responsiveness during low-displacement excitations. Addressing these challenges requires careful system-level optimization and the development of smart hydraulic controls that balance energy harvesting with suspension performance [29].

E. *Other Transduction Mechanisms*

Other transduction techniques have been proposed for niche or low-power scenarios:

- Electrostatic harvesters, suitable for MEMS devices, use varying capacitance between vibrating plates to produce energy. These systems often require an external bias voltage and are difficult to scale for vehicles [27].
- Triboelectric generators rely on contact electrification between different materials. While showing potential in laboratory settings, these devices face durability and stability issues under real driving conditions [28].
- Hybrid harvesters, combining piezoelectric and electromagnetic mechanisms, offer a broader frequency response and increased total energy yield, though at the cost of higher system complexity [29].

These emerging approaches demonstrate growing innovation in the field but are not yet widely implemented in automotive-scale systems.

Among these alternative mechanisms, electrostatic harvesters have primarily been explored in micro-scale systems such as MEMS and wearable electronics. Their operation is based on changes in capacitance caused by relative displacement between electrodes. Despite their compact structure and ease of integration, they face serious limitations for vehicle-scale applications due to the requirement of a priming voltage and sensitivity to environmental noise [30].

Triboelectric generators (TEGs), on the other hand, utilize the triboelectric effect — a type of contact electrification — to generate power. These systems involve repeated friction or contact between different dielectric materials. TEGs have demonstrated promising results in lab-scale tests, particularly for low-frequency harvesting, but their long-term stability and durability under vibration, moisture, and temperature cycling are still under investigation. Furthermore, issues like material fatigue and surface wear hinder large-scale automotive use [31].

Hybrid transduction approaches, combining piezoelectric and electromagnetic effects, are now gaining traction in advanced prototypes. These designs aim to capitalize on the high voltage output of piezoelectric materials and the high current capability of electromagnetic systems. By leveraging both effects in one structure, they extend the operational frequency bandwidth and enhance total harvested energy [32]. However, these designs typically suffer from increased system complexity, intricate signal conditioning requirements, and bulkier form factors, which currently limit their commercial scalability.

Table 1 presents a comparative evaluation of various kinetic energy harvesting (KEH) suspension mechanisms studied in recent literature. It outlines the type of suspension system, vehicle application, average or peak power output, energy recovery efficiency, and notable advantages and limitations for each mechanism.

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. SUSPENSION SYSTEM ARCHITECTURES AND ENERGY DISSIPATION DYNAMICS

Vehicle suspension systems serve dual roles: isolating passengers from road disturbances and maintaining tire contact for optimal traction. These systems dissipate significant vibrational energy, primarily as heat, through damping elements such as shock absorbers and struts. Understanding the energy flow within different suspension architectures is essential for integrating effective kinetic energy harvesting mechanisms.

Traditional suspension systems are categorized based on their operational strategy into passive, semi-active, and active architectures. Passive suspensions use fixed damping and spring constants and are the most commonly used due to their simplicity and cost-effectiveness. However, they lack adaptability and often result in energy loss as heat during dynamic travel conditions. In contrast, semi-active suspensions utilize variable damping elements such as magnetorheological (MR) or electrorheological (ER) dampers, which allow real-time tuning of damping force but still require external control inputs and power [33].

Active suspensions employ actuators that apply counteracting forces independent of road inputs, offering superior ride comfort and handling performance. These systems consume significant energy but also provide more opportunities for kinetic energy recovery when integrated with suitable transducers. Advanced active systems, such as the keROT architecture used in high-end vehicles, can simultaneously regulate ride dynamics and harvest energy from suspension motion.

From an energy perspective, suspension systems are primarily dissipative, converting vibrational energy into heat through hydraulic or frictional damping. Research indicates that a standard mid-sized passenger vehicle operating under average urban conditions dissipates approximately 100–400 W of energy through its suspensions [34]. Harvesting even a fraction of this energy could power auxiliary systems or sensors, thereby improving vehicle energy efficiency without compromising ride quality.

To optimize energy harvesting, it is essential to analyse energy flow pathways, identify dominant modes of energy loss, and match harvester response to the vehicle's frequency and displacement characteristics. This systems-level understanding is foundational for the successful integration of KEH into both conventional and next-generation suspension designs.

A. Passive Suspension Systems

Passive suspensions are the most common configuration in conventional vehicles. They employ fixed-parameter components such as springs and dampers with no external power input or adaptability [1]. The damper dissipates vibrational energy by forcing fluid through orifices in a piston cylinder, converting mechanical motion into thermal energy [2].

Though reliable and cost-effective, passive systems are inherently energy-wasting. Studies show that in stop-and-go driving conditions, these systems dissipate 100–400 W of vibrational energy per wheel [3]. As they cannot adjust their damping characteristics in real time, energy recovery potential is high but untapped [4].

Despite their limitations, passive suspensions remain the industry standard due to their simplicity, reliability, and low production cost. They are mechanically robust and require minimal maintenance, which makes them especially favourable for economy vehicles, commercial fleets, and off-road applications. However, their inability to adapt to varying road conditions results in sub-optimal damping performance, particularly when transitioning between smooth and rough terrain or during variable-speed travel.

From a kinetic energy harvesting perspective, passive systems offer a consistent mechanical motion profile ideal for energy conversion. Each vertical movement of the wheel and chassis assembly generates repetitive, oscillatory input to the damper—most of which is lost as heat. This recurring motion provides a reliable mechanical excitation source for both linear and rotational harvesters, especially electromagnetic and piezoelectric types.

Various studies have explored embedding retrofit harvesters into passive suspension units without altering the primary mechanical behaviour. For instance, rack-and-pinion and ball-screw generators have been successfully integrated into passive struts, enabling energy harvesting during compression and rebound strokes without affecting damping rates [5], [6]. Such retrofits allow vehicles to maintain their original suspension characteristics while benefiting from additional energy output, making them an ideal platform for early-stage KEH deployments.

Moreover, as passive suspensions dominate the global vehicle fleet, they present a massive untapped opportunity for low-cost, scalable implementation of KEH systems—particularly in regions or sectors where upgrading to active suspension remains economically unfeasible.

B. Semi-Active Suspension Systems

Semi-active suspensions use adjustable dampers (e.g., magnetorheological or electrohydraulic) that respond to road conditions or control inputs while consuming minimal power [5], [6]. These systems modulate damping forces in real time without adding energy to the system, offering improved ride comfort and road handling [7].

By integrating KEH with semi-active suspensions, the energy harvested could be used to partially or fully power the control electronics, creating closed-loop self-powered smart suspensions [8]. However, complexity and control requirements increase with integration [9].

Semi-active suspensions strike a balance between the simplicity of passive systems and the responsiveness of active configurations. They adjust their damping characteristics dynamically through variable valves, controlled electromechanical actuators, or smart fluids, typically without contributing additional energy to the motion. This allows them to modulate force output based on vehicle speed, load distribution, or terrain feedback, leading to enhanced ride quality and reduced component fatigue [10].

One of the most studied configurations in this category is the magnetorheological (MR) damper, which uses fluids whose viscosity changes in response to magnetic fields. This allows instantaneous control of damping levels and opens opportunities for dual-functionality — acting both as a damper and a generator. When designed appropriately, the same motion that adjusts damping can also induce electrical output through embedded coils and magnetic circuits [11].

In terms of energy harvesting, semi-active suspensions present a unique integration challenge: harvested power is typically modest (tens of watts), yet the system's control electronics require precise and stable power. This has led to interest in self-powered feedback loops, where the energy harvested from suspension motion can sustain sensor modules, controllers, or communication circuits, especially in autonomous or sensor-rich platforms [12].

However, added complexity in sensing, computation, and energy management circuits increases overall system design and cost. Ensuring synchronization between energy harvesting and damping modulation, especially under real-time varying road dynamics, requires advanced control algorithms and robust power conditioning strategies.

C. Active Suspension Systems

Active suspensions use external actuators (electric, hydraulic, or pneumatic) to apply forces independent of suspension deflection [10]. These systems offer the highest level of control and ride quality but demand substantial power (500–1000 W per corner) [11].

While theoretically attractive for energy regeneration, these systems often require more energy to operate than they can recover. However, incorporating regenerative actuators or linear motors can partially offset energy consumption under certain conditions, especially in bump and rebound phases [12], [13].

Active suspensions enable full control over chassis dynamics by applying force inputs that are not dependent on road excitations. This allows for independent tuning of ride height, pitch, roll, and vertical stiffness, making them ideal for high-performance vehicles, military transport, and next-generation autonomous platforms. Examples include electrohydraulic systems like Bose's active suspension and electromechanical designs using high-force linear motors [14].

Although these systems offer unmatched comfort and handling, they are typically net energy consumers due to the high demand placed on their actuators. However, recent developments in regenerative active suspensions propose using linear electromagnetic motors that act alternately as actuators and generators — recovering energy during suspension movement while still providing force output. This is especially useful during downward (bump) strokes or terrain-induced oscillations, where the actuator can switch into generator mode without compromising ride control [15].

One promising configuration is the eROT system developed by Audi, which replaces conventional dampers with horizontally mounted electromechanical rotary actuators. This setup captures suspension motion more efficiently due to its favourable mechanical leverage and is capable of producing over 100 W per suspension unit during normal driving [16]. Similarly, other linear motor-based systems demonstrate dual-mode operation with real-time switching between active damping and harvesting states.

Despite their promise, challenges remain in achieving real-time power balance, integrating reliable control electronics, and minimizing losses during switching operations. Nonetheless, regenerative active suspensions represent the cutting-edge frontier in KEH integration, blending control, comfort, and energy recovery into a unified architecture.

D. Suspension Topologies for KEH Integration

The effectiveness of KEH depends not only on suspension type but also on topology. Key designs include:

- Double wishbone suspension: Offers well-defined vertical movement paths, allowing easy placement of linear harvesters [14].
- McPherson strut: Compact and widely used, but has limited vertical stroke, reducing potential harvester amplitude [15].
- Trailing-arm and leaf spring systems: Common in heavy-duty vehicles, offering higher vertical travel and force transmission, favoring KEH installation [16].

Proper selection of KEH placement is crucial. Mounting between unsprung and sprung masses (e.g., on the shock absorber or between the control arm and chassis) yields maximum relative displacement for harvesting [17].

Beyond identifying suitable suspension architectures, maximizing KEH performance also requires a deep understanding of mechanical motion paths and the directionality of force transmission. The vertical travel amplitude, relative motion between chassis and wheel assembly, and system stiffness directly influence the feasibility of energy harvesting at specific suspension nodes. For example, suspensions with high vertical stroke, such as leaf-spring or trailing-arm setups, are inherently better suited for linear KEH devices that rely on displacement magnitude for effective transduction [18].

In contrast, systems like the McPherson strut, while compact and cost-effective, present limited displacement range, which constrains harvester integration unless supplemental mechanisms (e.g., motion amplifiers or mechanical converters) are introduced. However, their ubiquity in modern passenger vehicles makes them a valuable target for scalable, low-profile KEH retrofits, particularly electromagnetic rotary systems integrated into the damper body.

The double wishbone suspension provides a more favourable mechanical layout for harvester placement, as it offers greater design flexibility and multiple mounting points with predictable relative motion. Linear harvesters can be installed between upper/lower control arms and the vehicle chassis, capturing motion along vertical or angular trajectories. Moreover, the parallelogram-like motion enables better kinematic modelling and control of harvester performance in both simulation and hardware.

Importantly, optimal KEH integration requires careful attention to unsprung mass influence, suspension stiffness, and resonance behaviour. Mounting the harvester between the unsprung and sprung masses — such as on the damper shaft or between a trailing arm and the vehicle frame — maximizes displacement and force transmission, yielding higher energy conversion without affecting suspension dynamics adversely [19].

E. Energy Flow and Dissipation Mapping

Energy within a suspension system is partitioned into elastic potential (stored in the spring), kinetic (mass motion), and dissipative (heat via damping) components. The goal of KEH is to intercept and convert part of the dissipative energy without compromising ride comfort [18].

Dynamic simulations using vehicle models (quarter-car, half-car, or full-car) and tools like MATLAB/Simulink or CarSim are used to estimate energy recovery potential [19]. Real-world measurements indicate that between 100 W and 400 W per wheel can be theoretically harvested on uneven terrain without deteriorating vehicle dynamics [20].

Accurate mapping of energy flow within the suspension system is essential for identifying harvesting potential and evaluating system efficiency. Typically, the total mechanical input from road-induced excitations is distributed among spring deformation (elastic storage), damper dissipation (heat), and body/chassis acceleration (kinetic energy). In conventional suspensions, over 60–70% of this input is lost in the form of heat, presenting a valuable opportunity for conversion via KEH mechanisms [21].

To quantify this, researchers employ multi-DOF (degrees-of-freedom) vehicle models that simulate vertical and angular dynamics of the vehicle body. These models integrate real-time road profiles and suspension geometry to compute force–displacement relationships and power dissipation rates across suspension elements. Quarter-car models offer a simplified yet effective platform to isolate single-wheel responses, while full-car models are necessary for evaluating ride comfort, pitch, and roll impacts under KEH integration [22].

Simulation environments such as MATLAB/Simulink enable coupling of suspension dynamics with transducer behaviour — e.g., modelling electromagnetic coil response or piezoelectric current output under varying displacement amplitudes and frequencies. When calibrated with road test data, these simulations can predict system-level energy yield and efficiency across different road classes (urban, highway, off-road).

Experimental studies confirm that uneven terrain and aggressive driving significantly increase the available vibrational energy, especially in commercial vehicles and buses. For example, dynamic testing on cobbled or unpaved roads has shown peak power values exceeding 500 W per suspension unit under transient excitations, albeit with greater design stress and packaging constraints [23].

IV. ADAPTIVE RESONANCE TUNING IN KINETIC ENERGY HARVESTING SUSPENSIONS

To maximize energy output, most vibration-based KEH systems are designed to operate near their resonant frequency. However, real-world driving conditions introduce a wide spectrum of excitation frequencies, driven by vehicle speed, load variation, and road roughness. To address this, adaptive resonance tuning mechanisms are developed to dynamically match the harvester’s natural frequency to the dominant excitation frequency.

Adaptive tuning strategies can be broadly categorized into mechanical, electrical, and control-based approaches.

Mechanical tuning methods involve modifying the system’s physical parameters—such as stiffness or mass—to shift the natural frequency. Techniques include the use of variable stiffness springs, preloaded elements, or mechanical biostability. For instance, systems employing nonlinear geometries or buckled beam structures can offer a wider operational frequency range, allowing the KEH device to respond effectively across diverse road profiles [24]. Some designs utilize movable proof masses or magnetic repulsion forces to alter resonance in real time without requiring external energy.

Electrical tuning, on the other hand, adjusts the load impedance or modifies the circuit resonance to optimize energy transfer from the transducer. This is commonly applied in piezoelectric harvesters where resonant matching of electrical and mechanical domains is critical. Tunable inductors, variable capacitors, and synchronized switching techniques (e.g., Synchronized Switch Harvesting on Inductor – SSHI) are examples of passive or semi-active strategies that enable frequency adaptability with minimal power overhead [25].

Control-based tuning strategies use sensors and algorithms to monitor excitation frequency in real-time and adjust system parameters accordingly. In electromagnetic systems, this might involve controlling damping force through active circuitry or feedback loops that regulate generator load resistance. Smart KEH systems have been demonstrated with real-time frequency tracking algorithms, enabling on-the-fly optimization of energy output during fluctuating driving conditions [26].

These adaptive tuning methods are especially relevant for broadband or stochastic road excitations, where fixed-frequency harvesters underperform. While they introduce added complexity, adaptive systems significantly enhance harvester robustness, efficiency, and responsiveness, making them vital for commercial-scale deployment in dynamic vehicular environments.

Mechanical tuning methods involve modifying the system’s physical parameters—such as stiffness or mass—to shift the natural frequency. Techniques include the use of variable stiffness springs, preloaded elements, or mechanical bistability. For instance, systems employing nonlinear geometries or buckled beam structures can offer a wider operational frequency range, allowing the KEH device to respond effectively across diverse road profiles [24]. Some designs utilize movable proof masses or magnetic repulsion forces to alter resonance in real time without requiring external energy.

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F. Mechanical Tuning Methods

Mechanical tuning alters the physical properties of the harvester's structure to adjust its natural frequency. Key strategies include:

- Variable stiffness mechanisms: Springs with controllable geometry or material properties (e.g., nonlinear beams, bistable configurations) shift resonance in real-time [1], [2].
- Movable proof masses: Adjusting the location or magnitude of the oscillating mass dynamically alters system inertia and, hence, resonance [3], [4].
- Preload tuning: Axial or torsional pre-stress applied to the harvester can stiffen or soften the response depending on loading direction [5].

These systems are entirely passive or minimally actuated, consuming negligible power, but their tuning range is often limited and slow to respond to rapid vibration shifts [6].

Mechanical tuning approaches are attractive due to their simplicity, low energy consumption, and mechanical robustness. Devices based on buckled beams, clamped–clamped arches, and compliant mechanisms have demonstrated enhanced bandwidths and resonance modulation without electronic control. These structures exploit geometric or material nonlinearities to produce multiple stable states or softening/hardening behaviour that shifts the effective natural frequency during operation [7].

Movable proof mass systems are particularly effective in applications with predictable excitation profiles, such as suspension systems subject to load-dependent vibrations. By shifting the position of the mass relative to the base structure—either passively under centrifugal force or via small actuators—the resonance condition can be finely adjusted to match the excitation spectrum. This principle has also been adapted in magnetically suspended proof masses that allow non-contact tuning through repulsive/attractive forces [8].

Preload-based tuning offers another passive solution by changing internal strain conditions. By adjusting axial tension or applying torsional bias, the stiffness of cantilever or beam structures can be dynamically modified. This is particularly useful in systems using shape memory alloys (SMAs) or elastomers that exhibit stress-dependent stiffness, though the response time and durability remain key limitations [9].

While mechanical tuning systems offer high reliability and low energy overhead, they tend to have narrow dynamic responsiveness and require physical motion or structural deformation, which can delay adaptation under rapidly changing driving conditions. Thus, they are often combined with electrical or control-based strategies to achieve more responsive and adaptable KEH solutions.

G. Electromechanical Tuning Methods

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

- Magnetorheological and electrorheological fluids: Their effective damping and stiffness change under electromagnetic or electric fields, offering fast, reversible tuning [7], [8].
- Piezoelectric shunt tuning: An external electrical circuit connected to piezoelectric elements modifies dynamic stiffness and broadens frequency response [9].
- 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.

H. Active and Control-Based Tuning

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

- Proportional–Integral–Derivative (PID) control: Simple but effective for systems with well-understood dynamics [13].
- Sliding Mode Control (SMC): Robust under varying system parameters and disturbances, suitable for real-time suspension adaptation [14].
- Fuzzy logic and artificial neural networks (ANNs): Handle nonlinearities and uncertainties in vibration environments [15], [16].
- 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.

I. Self-Tuning and Passive-Active Hybrid Systems

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

- Mechanical tuning via bistable structures, complemented by microcontroller-based resonance detectors, allows rapid frequency alignment without full-time actuation [20].
- 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. PERFORMANCE EVALUATION, IMPLEMENTATION CHALLENGES, AND FUTURE OUTLOOK

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.

J. 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.

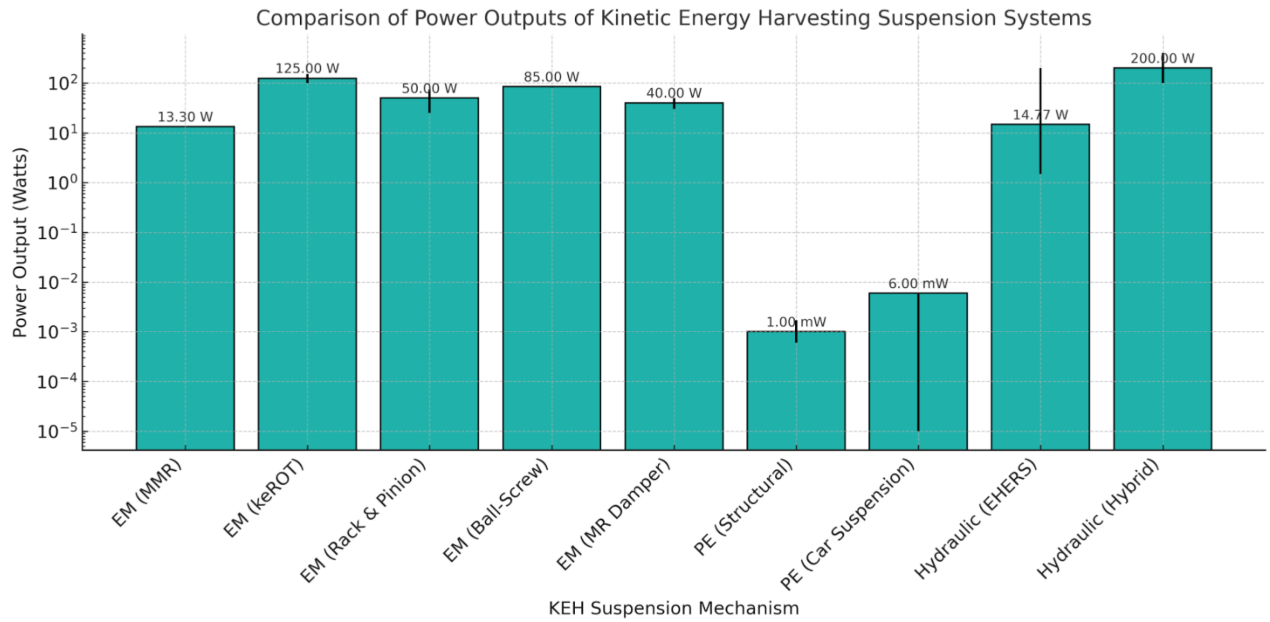

Figure 1. Comparison of Power Outputs of Kinetic Energy Harvesting Suspension Systems

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

- A mechanical motion rectifier (MMR)-based suspension system recovered up to 150 W per wheel under rough-road excitation at 2.5 Hz [1].
- Piezoelectric multilayer devices embedded in suspension struts generated 250–350 µW at 30–50 Hz, sufficient to power wireless sensor nodes [2], [3].
- A hydraulic-electromagnetic hybrid system installed on a city bus produced 14.7 W average power in real-world driving tests [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:

- Electromagnetic harvesters: 40–70%, depending on magnetic circuit design and rectification topology [7].
- Piezoelectric harvesters: 30–60%, especially with impedance-matched shunt circuits [8].

- 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.

K. Factors Influencing KEH Performance

Several variables significantly affect energy output:

- Excitation profile: Vibration amplitude, frequency content, and road roughness determine the available mechanical energy [6].
- Vehicle mass and speed: Heavier vehicles and faster speeds typically increase vibrational input [7].
- Harvester location and design: Mounting position (e.g., between control arm and chassis) directly influences relative displacement and strain [8].
- 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].

L. Implementation Challenges

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

- Mechanical durability: Moving parts in electromagnetic or hydraulic harvesters are prone to wear, leakage, and fatigue under prolonged exposure to shocks and moisture [11].
- Integration complexity: Retrofitting KEH into existing suspension systems requires redesigning suspension geometry, affecting safety and certification processes [12].
- Mass and space constraints: Additional components increase unsprung mass, potentially worsening handling and ride comfort [13].
- Energy trade-offs: In some systems, energy recovered is offset by increased rolling resistance or system damping [14].

- 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].

M. Future Research and Development Opportunities

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

- Lightweight designs using advanced composites and integrated structures to reduce mass and maintain suspension performance [16].
- AI-based adaptive controllers for real-time tuning of resonance, energy routing, and predictive maintenance [17].
- Hybrid energy harvesting systems that combine electromagnetic and piezoelectric methods for broader bandwidth and enhanced efficiency [18].
- Modular and scalable architectures allowing plug-and-play KEH units adaptable to various vehicle platforms [19].
- 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 review has presented a comprehensive evaluation of kinetic energy harvesting (KEH) via adaptive suspension resonance in vehicles. Various transduction mechanisms—including electromagnetic, piezoelectric, hydraulic, and hybrid systems—offer distinct advantages depending on specific power demands, dynamic conditions, cost considerations, and target vehicle platforms. Each mechanism exhibits unique performance trade-offs, and their effectiveness depends not only on intrinsic material and transducer properties but also on suspension topology, excitation profile, and real-world deployment constraints.

The integration of adaptive resonance tuning strategies—mechanical, electromechanical, and intelligent control-based—has demonstrated significant potential in improving energy capture efficiency under dynamic road conditions. Mechanical tuning approaches offer low-power adjustability, while electromechanical and control-based systems provide real-time adaptability, albeit at the cost of higher complexity and power overhead. Hybrid architectures that combine passive and active control loops appear particularly promising for creating robust, scalable, and energy-efficient KEH systems.

Despite substantial advancements in modelling, simulation, and prototype validation, the transition from laboratory-scale experimentation to large-scale vehicular integration remains constrained. Challenges such as system durability, packaging constraints, electromagnetic interference, fluid losses in hydraulic units, and increased unsprung mass continue to hinder practical implementation. Moreover, manufacturing cost, regulatory compliance, and retrofitting compatibility must be addressed before widespread adoption becomes feasible.

Nevertheless, ongoing innovations in lightweight composites, printed piezoelectric materials, ultra-low-power electronics, and AI-driven tuning algorithms present transformative opportunities. With the automotive industry moving rapidly toward electrification, autonomous operation, and intelligent vehicle networks, KEH-enabled suspensions may evolve beyond energy harvesting into multi-functional systems that combine energy recovery, self-powered sensing, and adaptive ride control.

In conclusion, KEH-equipped suspension systems represent a compelling frontier in vehicular energy sustainability. Continued interdisciplinary research—spanning materials science, automotive dynamics, power electronics, and embedded AI—will be instrumental in enabling robust, modular, and self-powered KEH platforms capable of powering the next generation of smart, efficient, and autonomous vehicles.

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, Vinod Bodhale contributed to data collection, technical discussion, and manuscript review. All authors reviewed and approved the final version of the manuscript.

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