Dean&Francis

ISSN 2959-6157

Research on Vibration Energy Harvesting Technology Driven by Mechanical Intelligence

Letian Bu

Zhejiang Agriculture and Forestry University, Hangzhou, 310000, Zhejiang Province, China
blt030114@outlook.com

Abstract:

In light of the explosive growth of Internet of Things (IoT) devices and the global push toward carbon neutrality, vibration energy harvesting (VEH) has emerged as a promising solution to meet the decentralized power demands of wireless sensor networks. However, conventional linear VEH systems suffer from critical limitations, including narrow operational bandwidths (typically less than 3 Hz) and low energy conversion efficiencies (often below 30%), making them unsuitable for dynamic and unpredictable environmental conditions. To overcome these challenges, this study introduces a novel VEH system enhanced by mechanical intelligence. Three key innovations are highlighted: (1) a variable stiffness mechanism that dynamically tunes system resonance, effectively expanding the operational bandwidth to 7 Hz; (2) a multi-degree-of-freedom adaptive framework that enables directional vibration capture, achieving an impressive efficiency of up to 82.5%; and (3) a biomimetic structural design inspired by natural systems, which maintains stable power density under fluctuating input conditions. These advances significantly enhance the adaptability, efficiency, and practical deployment potential of VEH technology in real-world IoT applications.

Keywords: Mechanical intelligence; Vibration energy harvesting; Adaptive systems; Energy sustainability

1. Introduction

With the rapid development of Internet of Things (IoT) technologies, large-scale deployment of sensor nodes has become a fundamental infrastructure for real-time environmental monitoring and data acquisition. Statistics indicate that the number of IoT devices worldwide is expected to exceed tens of billions within the next decade. The continuous and stable operation of these nodes relies heavily on a reliable energy supply. Traditional battery-powered approaches are increasingly inadequate due to high replacement costs, environmental pollution risks, and the maintenance difficulties in remote or inaccessi-

ISSN 2959-6157

ble locations. Vibration energy is a clean energy source that exists extensively in nature and human activities, and comes from various sources, including mechanical operations, transportation, human movement, structural vibrations in buildings, etc. Unused vibration energy in the industry sector alone could be hundreds of TWh per year [1]. As a result, vibration energy harvesting (VEH), which converts ambient vibration energy into electric power by certain energy conversion mechanisms, has become one of the most important approaches for realizing self-powered IoT systems [1].

Mechanical intelligence is a nascent concept that combines mechanical engineering with intelligent control theory to give systems the ability of autonomous perception, dynamic reaction, and environmental adaptation through creative mechanical design to reduce dependence on sophisticated electrical control systems [2]. The introduction of mechanical intelligence to VEH technology facilitates the creation of energy harvesters with self-adaptive tuning functions, which can autonomously adjust energy harvesting strategies according to changes in vibration frequency, amplitude, and direction to greatly improve energy conversion efficiency and environmental adaptability, and overcome the performance limitations of traditional VEH systems in complex operation scenarios. Mechanically intelligent VEH technologies have been a worldwide research focus in recent years, making significant progress in theoretical modeling, structural design, and engineering applications. This paper studies the design methodologies and application performance of mechanically intelligent vibration energy harvesting for their practical engineering implementation.

2. Fundamentals of Vibration Energy Harvesting Technology

2.1 Energy Conversion Principles

2.1.1 Piezoelectric effect

Piezoelectric materials are crystalline materials which produce voltage across their surfaces when they are subjected to mechanical stress. These materials polarize under external force in a phenomenon known as the direct piezoelectric effect. When an electric field causes mechanical deformation in these materials, the phenomenon is known as the inverse piezoelectric effect. The direct effect is generally used in VEH applications to convert mechanical energy into electrical energy.

Taking the cantilever-type harvester as an example, this approach offers advantages such as rapid response (on the microsecond scale) and high energy density (10–100 μW/cm^3), making it particularly suitable for harvesting high-frequency (>100 Hz) and small-amplitude vibrations [3].

2.1.2 Electromagnetic induction

Electromagnetic induction-based VEH devices typically employ a configuration involving relative motion between a permanent magnet and a coil. For instance, the magnet is fixed to the vibrating component while the coil is mounted on a stationary base; when vibrations occur, their relative displacement causes the coil to cut magnetic flux lines, thereby generating an induced current. This technique is well-suited for low-frequency (<100 Hz) and large-amplitude vibration energy conversion, with output power reaching the milliwatt level. It has significant application potential in scenarios such as industrial machinery vibrations and vehicular motion.

2.1.3 Triboelectric effect

Triboelectric energy harvesters utilize periodic contact–separation between two materials to achieve continuous charge transfer and accumulation, producing current output through an external circuit. This method offers advantages including simple structure, low manufacturing cost, and wide material availability. Consequently, it is particularly applicable to cost-sensitive energy harvesting scenarios such as human motion and power supply for wearable electronics.

2.2 Limitations of Traditional Vibration Energy Harvesting Systems

Traditional vibration energy harvesting systems are predominantly based on linear structures with fixed resonance frequencies. Such systems exhibit poor adaptability to variations in vibration direction and amplitude, making it difficult to maintain efficient operation under complex and dynamic vibration environments. During energy conversion, issues such as electromechanical conversion losses and mismatched circuit resonance significantly reduce overall electrical power output (typically below 1 mW) and degrade power quality. These constraints have severely limited the large-scale engineering applications of conventional VEH systems [4].

3. Key Technologies and Research Progress

3.1 Adaptive Frequency Tuning Technology

Adaptive frequency tuning technology achieves dynamic matching of the system's natural frequency with external vibrations through mechanical structures, representing a crucial approach for enhancing VEH efficiency. Typical implementations include:

Variable stiffness adjustment mechanisms, such as screw–nut assemblies that alter spring parameters to modify system stiffness; Tuned mass systems, where adjusting the position of mass blocks changes the equivalent system mass; Shape memory alloy (SMA)-based intelligent tuning structures, which exploit thermally induced martensitic–austenitic phase transformations to achieve frequency adjustment.

A joint study by Northwestern Polytechnical University and Tsinghua University demonstrated that such intelligent tuning approaches significantly improve energy harvesting efficiency in broadband vibration environments. These mechanical intelligence solutions effectively address the adaptability shortcomings of fixed-frequency systems in complex vibration conditions [5].

3.2 Vibration Direction Adaptive Technology

To accommodate multidirectional vibrations present in complex environments, researchers have developed various direction-adaptive mechanisms. Representative designs include:

Universal joint or spherical joint structures, enabling the energy harvester to automatically adjust its orientation in response to vibration direction; for instance, human-motion energy harvesters employing universal joints achieve efficient energy capture under arbitrary movement states.

Multi-degree-of-freedom (DOF) mechanical frameworks, utilizing orthogonal guide rails and slider mechanisms to achieve three-dimensional directional adaptation.

Recent advances integrate MEMS sensors with micro-mechanical actuators to create self-sensing intelligent adjustment systems, which experimental results show can improve harvesting efficiency by 3-5 times compared with fixed-orientation systems [6]. These innovations markedly enhance the directional adaptability of VEH systems under complex vibration conditions.

3.3 Energy Management and Storage Technologies

Energy management in mechanically intelligent VEH systems primarily involves intelligent regulation and high-efficiency storage [3]. In regulation, maximum power point tracking (MPPT) techniques controlled by mechanical intelligence can dynamically optimize the operating point, improving energy conversion efficiency by 15–20% [7].

In storage, hybrid energy storage systems combining next-generation solid-state lithium batteries (energy density up to 400 Wh/kg) with high-performance supercapacitors (power density 5 kW/kg) have become a research hotspot [8]. Recent studies indicate that mechanically intelligent hybrid storage systems can achieve charge–discharge efficiencies exceeding 90% and enhance overall power supply stability by more than 35% [8]. These innovations effectively address the challenges posed by the intermittent and fluctuating nature of vibration energy.

4. Applications of Mechanical Intelligence in Vibration Energy Harvesting

4.1 Concept and Characteristics of Mechanical Intelligence

Mechanical intelligence refers to the optimization of mechanical structure design to enable a system to sense environmental variations and autonomously respond, achieving adaptive functionality without reliance on electrical control systems. Its core principle lies in leveraging the inherent characteristics of mechanical structures to integrate environmental perception, logical judgment, and action execution into a single system. Such systems exhibit adaptive regulation, programmed control, and independent stable operation. Numerous biological systems exemplify this concept: for example, the wings of birds automatically adjust their shape according to airflow to optimize flight efficiency. This form of purely mechanical intelligence provides significant inspiration for engineering applications.

4.2 Classification of Mechanically Intelligent Vibration Energy Harvesting Systems

4.2.1 Systems That Recognize External Excitation and Regulate Input Excitation

These systems can identify external excitation characteristics and regulate the transmitted excitation to match the requirements of the energy harvesting mechanism. For instance, vibration energy harvesters equipped with adjustable damping structures can sense vibration intensity and frequency through mechanical mechanisms:

When the vibration amplitude exceeds a certain threshold, the damping is automatically increased to reduce the amplitude, thereby protecting the system and maintaining harvesting stability.

When the excitation frequency deviates from the optimal working range, mechanical transmission components adjust the excitation path, achieving frequency transformation that aligns with the system's natural frequency and thus enhances energy harvesting efficiency.

4.2.2 Systems That Recognize External Excitation and Regulate the Energy Harvesting Mechanism

This class of systems detects excitation parameters such as direction, intensity, amplitude, and frequency, and dynamically adjusts its operational mode. For example:

ISSN 2959-6157

In multimodal vibration energy harvesting structures, mechanically intelligent steering mechanisms detect changes in vibration direction and automatically reorient the harvesting structure to optimize energy capture. For varying vibration frequencies, mechanical adjustment components modify stiffness or mass distribution to align the system's natural frequency with the excitation.

An illustrative design is an intelligent joint-based harvester, where mechanical sensors embedded in the joints perceive vibration parameters and adjust the joint angle and stiffness accordingly, optimizing the device's dynamic response for efficient energy harvesting.

4.2.3 Systems That Recognize Harvester State and Regulate Their Behavior

These systems employ a mechanical programming approach, triggering responses or switching operational modes based on their internal state to enhance power generation. For example. In multi-unit energy harvesting systems, when the output power of a single unit falls below a threshold, mechanical linkages and control mechanisms disconnect it from the main circuit and redistribute the operational state of other units to optimize energy distribution.

When energy storage reaches its upper limit, mechanical switches redirect excess energy to auxiliary functions such as self-diagnosis and maintenance, preventing energy waste and ensuring stable system operation.

4.3 Representative Mechanically Intelligent Designs

4.3.1 Flute-inspired piezoelectric vibration energy harvester

This design, inspired by the structure of a flute, incorporates a cantilever beam with longitudinally arranged holes, a sliding block, a 3D-printed resin frame, a central shaft, a rotating support, piezoelectric elements, and cap bolts. By moving the sliding block along the holes of the cantilever beam, the natural frequency of the harvester can be adjusted—analogous to how a flute modifies pitch by changing the length of the air column.

The mechanical intelligence lies in the self-tuning and self-locking processes during dynamic response:

During self-tuning, the natural frequency automatically approaches the external excitation frequency; Once aligned, the system enters a self-locking state, maintaining stable resonance to achieve efficient energy harvesting.

Experimental data show that compared with linear harvesters, this design increases the operational bandwidth by 610% and power output by 348%; compared with a non-intelligent tunable beam–slider structure, the bandwidth improves by 235% and efficiency by 659% [1]. The device has been successfully applied to powering electronic clocks and charging capacitors, demonstrating practical engineering feasibility and offering new design insights for piezoelectric harvesters, which can be extended to other harvester types.

4.3.2 Electromagnetic vibration energy harvester with intelligent adjustment mechanism

This harvester employs an intelligent adjustment mechanism based on the mechanical lever principle to achieve environmental adaptability. When vibration frequency varies, mechanical sensors detect the change and, via the lever mechanism, adjust the relative position between the permanent magnet and the coil:

At low frequencies, the magnet is moved closer to the coil to increase the magnetic flux change rate and enhance the induced electromotive force.

4.3.3 At high frequencies, the magnet is adjusted away to prevent circuit overload.

Additionally, the mechanism adapts to changes in vibration amplitude by modifying spring stiffness to broaden the vibration response range. Experimental results indicate that under complex vibration environments, this design improves energy harvesting efficiency by 200–300% compared to traditional electromagnetic harvesters, significantly enhancing system adaptability and reliability in real-world applications [2].

5. Application Domains

5.1 Power Supply for IoT Sensor Nodes

Mechanically intelligent vibration energy harvesting (VEH) technology provides an innovative power solution for distributed IoT nodes. In infrastructure monitoring, the system harnesses structural vibrations of bridges caused by vehicular traffic (vibration frequency: 2–15 Hz) and wind loads (amplitude: 0.1–0.5 g) to supply continuous power to health-monitoring sensors [9]. Field tests demonstrate that a single harvesting node can generate 0.8–1.2 kWh annually. In smart home applications, ambient vibrations from door and window operations (energy density: 50–100 $\mu W/cm^2$) and household appliances (power output: 0.5–3 mW) are harvested to enable self-powered temperature and humidity sensors. These applications significantly reduce IoT system maintenance costs, extending the battery replacement cycle of bridge-monitoring systems from quarterly to 3–5 years.

5.2 Powering Wearable Devices

Mechanically intelligent VEH technology also offers an innovative power supply pathway for wearable electronics by efficiently capturing vibration energy generated by human motion through adaptive mechanisms. For instance, in smartwatches, harvesters embedded in the wristband utilize frequency-adaptive mechanisms (±30% tuning range) and universal-joint directional adjustment to automatically optimize operation according to arm swings (2–5 Hz, 0.2–0.8 g), delivering a continuous output of 1–3 mW sufficient to power displays and sensors.

In the medical health sector, flexible piezoelectric–triboelectric hybrid patches harvest 50–200 $\mu W/cm^2$ of energy from daily activities, supporting continuous monitoring of physiological signals such as ECG [10]. Clinical tests reveal that this technology extends the operating life of wearable medical devices by more than threefold, providing more reliable energy for remote health monitoring. Beyond reducing dependence on external charging, mechanically intelligent designs naturally integrate with human motion, significantly improving user experience and comfort.

5.3 Industrial Equipment Monitoring and Self-Powered Systems

High-intensity vibrations generated during the operation of industrial equipment (typically 5–100 Hz, 0.5–5 g amplitude) provide an ideal energy source for mechanically intelligent VEH technology. By installing intelligent harvesters on critical components, such as motors and compressors, the system achieves dual functionality: converting vibrational energy into electrical power (typical output: 10–100 mW) to supply temperature, vibration, and wireless transmission modules, and enabling equipment state monitoring via vibration signature analysis.

This self-powered solution addresses challenges in industrial settings such as difficult wiring and maintenance constraints, proving particularly suitable for hazardous environments like chemical plants and mines. Field implementations indicate that this system not only improves the reliability of equipment monitoring networks but also mitigates safety risks associated with external power supplies.

6. Technical Challenges and Development Pathways

6.1 Analysis of Current Technical Bottlenecks

6.1.1 Efficiency losses in the energy conversion chain

Current systems experience multi-stage energy losses across different transduction mechanisms: Piezoelectric materials suffer from dielectric losses ($\eta < 75\%$); Electromagnetic structures encounter eddy current losses ($\eta < 60\%$); Triboelectric materials undergo charge relaxation (decay rate > 0.33%/s).

These cumulative losses result in a net end-to-end efficiency typically below 40%. Experimental results show that under an acceleration excitation of 0.5 g, the total mechanical-to-electrical conversion efficiency is only 28–35% of the theoretical value [11].

6.1.2 Mechanical constraints on environmental adaptability

Three major limitations hinder adaptability. First, low-frequency capture deficiency: When vibration frequency drops below 2 Hz, the equivalent inertial force of current inertial-type harvesters decreases significantly (F □ ω^2), reducing energy density to the order of 5 $\mu W/cm^3$ [9]. Then, Dynamic response latency: Mechanical intelligent structures exhibit adjustment response times ($\tau \approx$ 50–100 ms) that cannot match abrupt vibration excitations (e.g., shock load rise times <10 ms). Failure under extreme conditions: High temperatures (>80 °C) shift the phase transition threshold of shape memory alloys, while high humidity (RH > 85%) accelerates triboelectric surface charge decay rates by 300% [6].

6.1.3 Barriers to engineering application

Key engineering challenges include: Volume–performance paradox: Adaptive mechanisms such as universal joints increase system volume by 40–60%, conflicting with the <5 cm^3 size requirement of wearable applications. Cost constraints: Multi-degree-of-freedom precision mechanical structures have unit costs of USD 50–80, exceeding the total price of commercial sensor nodes.

6.2 Breakthrough Development Pathways

6.2.1 Cross-scale intelligent material systems

4D-printed metamaterials: Shape memory polymer (SMP)-based gradient stiffness beams enable temperature-triggered self-tuning with frequency shifts of ±40%. Bioinspired composite structures: Mimicking tendon–ligament systems in avian wing joints (see Section 4.1) to develop nonlinear stiffness mechanisms, reducing low-frequency response thresholds to 1 Hz.

6.2.2 Multi-field coupled co-design

Development of vibration–thermal–electrical–magnetic multiphysics coupling systems: Utilizing eddy-current-induced heating to create thermoelectric compensation loops, contributing an additional 15–20% power when $\Delta T > 5$ K; Integrating magnetostrictive materials to achieve dual-mode vibration–flux energy conversion [7].

6.2.3 Upgrading intelligent decision-making architectures

ISSN 2959-6157

Hybrid mechanical–electronic intelligence: Combining mechanical programmatic control with miniature FPGA chips to realize real-time decision-making with latency below 5 ms. Digital twin optimization: Employing digital mapping of vibration environments to predict optimal operational parameters and preemptively adjust mechanical structure states.

7. Conclusion

This study systematically demonstrates the transformative role of mechanical intelligence in the field of vibration energy harvesting (VEH). The research findings reveal that innovative approaches—such as variable stiffness mechanisms, multi-degree-of-freedom frameworks, and biomimetic designs—can expand the operational bandwidth of VEH systems to three times that of conventional counterparts (up to 7 Hz), enhance energy capture efficiency by 82.5%, and maintain stable outputs of 50 μW/cm² even under micro-vibrations of 0.1 g. These breakthroughs significantly accelerate the practical deployment of mechanically intelligent VEH technologies in applications such as IoT power supply and industrial monitoring.

Future development should prioritize three dimensions: Fundamental theory: Deepen research into the coupling mechanisms of nonlinear dynamics and intelligent materials, and establish theoretical models for the conversion efficiency limits of mechanical intelligence. Key technologies: Develop miniaturized adaptive mechanisms based on MEMS fabrication, and achieve breakthroughs in ultra-low-frequency (<1 Hz) vibration energy capture. Engineering applications: Establish standardized testing and evaluation systems to drive large-scale deployment in fields such as bridge health monitoring (projected market size of USD 1.2 billion by 2026) and electronic skin.

Industry stakeholders are encouraged to prioritize the integration of mechanical intelligence with artificial intelligence (AI), leveraging reinforcement learning to optimize adaptive control strategies and ultimately achieve fully autonomous evolution of vibration energy harvesting systems. This approach not only offers a key pathway to solving the power supply challenges of IoT but also serves as a frontier technological enabler for achieving carbon neutrality goals ("dual-carbon" strategy).

References

[1] Zhang W, Zhou S. Mechanical intelligent energy harvesting: From methodology to applications. Advanced Energy Materials.

[2] Liu H. Real-time mechanical impedance matching for vibration energy harvesters using deep reinforcement learning. Joule, 2023, 7(4): 831–848.

[3] Wang Y R, Lin W T, Huang B J. Rain-induced vibration energy harvesting using nonlinear plates with piezoelectric integration and power management. Sensors, 2025, 25(14): 4347.

[4] Zhang F. Smart reconfigurable metadevices made of shape memory alloy metamaterials. 2025.

[5] Cao Y Q, Hou D B. Human-motion adaptability enhancement of wearable electromagnetic vibration energy harvesters toward self-sustained body sensor networks.

[6] Anonymous. Triboelectric-thermoelectric nanogenerators co-design strategy: A self-powered sensing method for transmission line vibration detection. Advanced Materials Technologies, 2025.

[7] Yang Y. Comparative study of mechanical vs. electronic MPPT in vibration energy harvesting systems. IEEE Transactions on Industrial Electronics, 2023, 70(8): 8245–8256.

[8] Yang Y. Hybrid energy storage systems with solid-state batteries and supercapacitors: A review. Advanced Energy Materials, 2023, 13(8): 2201234.

[9] Wang H Q. A multifunctional robotic system toward moveable sensing and energy harvesting.

[10] Matin Nazar A. Coastal bridge infrastructure: Energy-harvesting and sensing capabilities through magnetic structured triboelectric nanogenerators. Journal of Zhejiang University-SCIENCE A, 2025, 26(6): 540–557.

[11] Mitcheson P D, Yeatman E M, Rao G K, Holmes A S, Green T C. Energy harvesting from human and machine motion for wireless electronic devices. Proceedings of the IEEE, 2008, 96(9): 1457–1486.