



Footstep Based Piezoelectric Energy Harvesting System for Emergency Power Applications: A Review

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Abstract: The conversion of mechanical energy from vibrations or pressure to electrical energy is called piezoelectric energy harvesting. In the context of densely populated areas like railway stations, shopping malls, airports and underground transportation systems, the piezoelectric floor tiles have become a sustainable method to harvest the energy of people walking on the floor. This technology can be used to produce renewable energy directly from mechanical stress via piezoelectric materials. The emergency lighting system, evacuation guidance system and alarm systems are integral to modern buildings and underground transportation systems and can become inoperable during disasters or power failures. Recent studies have shown that potential applications of piezoelectric energy harvesting systems, LED exit signs, floor-guiding lights, sound alarms, and wireless safety devices are considered some of the low-power emergency uses. The harvested energy is usually stored by rectifiers and storage circuits for continuous operation under emergency situations. The working principles of piezoelectric energy harvesting frequently used piezoelectric materials, configurations of floor tiles, ways of storing the energy acquired, and application in emergency safety systems are discussed in this review paper. Recent developments, current challenges, and future research directions for energy harvesting applications of piezoelectric floor technologies in smart infrastructure and underground transport networks are reviewed.

Index Terms: Footstep Energy Generation, Piezoelectric energy harvesting, Piezoelectric floor tiles, Sustainable technology

1. INTRODUCTION

This growing need to have sustainable and resilient energy systems has stimulated researchers to find out about ambient energy harvesting as an additional alternative to traditional grid-dependent power supply. Energy harvesting technologies (EHT) capture small amounts of otherwise wasted energy (such as solar radiation, thermal gradients, electromagnetic fields, vibration and human motion) and convert it into electrical energy to drive low-energy devices [1] Of these technologies,

piezoelectric energy harvesting is particularly appealing due to the ability to directly convert mechanical stress, vibration, bending or pressure into electrical charge without the need to use rotating machinery or complex assemblies of electromagnetic components. This causes piezoelectric devices to be small, scalable and can be embedded into floors, pavements, shoes, wearable devices, bridges and sensor networks [2].

Motion in human footsteps, is a common repetitive and generally accessible mechanical energy source in the urban setting. In busy places like a railway station, airports, shopping malls, hospitals, universities, office towers and underground transit corridors experience thousands of footsteps/hours creating repetitive compressive loads that can be harvested with piezoelectric floor tiles or embedded arrays of transducer arrays [3].

Applications involving emergency power are a very suitable usage scenario since the occurrence of an evacuation event creates a concentrated human flow with grid power being either unavailable, or unreliable. Footstep energy can be used to power low-power emergency devices like LED path lights, exit indicators, buzzers, occupancy sensors and wireless safety nodes, piezoelectric tiles should be installed along evacuation routes, stairs, corridors and exits [4].

This review article will attempt to give a journal-type review of piezoelectric energy harvesting systems based on footsteps to generate energy which can be used in case of an emergency.

2. BASIC OF PIEZOELECTRIC ENERGY HARVESTING

Piezoelectricity is the property of some materials to produce electrical charge to the material which is subject to mechanical deformation. In the direct piezoelectric effect, the applied stress causes a displacement of the internal dipoles in the crystal of polymer structure, which results to electrical potential across the material electrodes. This effect is the operating principle of vibration-based, pressure-based and footstep-based energy harvesters.

Electromechanical systems Electrical behavior of a piezoelectric harvester is commonly modeled as an electromechanical system where mechanical input is coupled to an electrical output via material constants, capacitance, damping and load resistance. The amount of energy generated is highly dependent on the force applied, the magnitude of deformation, the excitation frequency, the coefficient of the material, mechanical boundary condition and electrical impedance [5].

Lead zirconate titanate (PZT), barium titanate (BaTiO_3), zinc oxide (ZnO) and polyvinylidene fluoride (PVDF) are the most utilized piezoelectric materials. This is due to the high piezoelectric coefficients of PZT, and its strong electromechanical coupling, which makes PZT highly popular in applications requiring flexibility, light weight, and greater fatigue tolerance in flexible or wearable applications [6].

In the case of floor-based systems, the material selection will have to balance the performance of the energy conversion, the mechanical durability of the material, the cost, the environmental stability and the safety. Higher output is provided by ceramic materials like PZT, but these materials are brittle, and polymer-based materials offer greater flexibility at the cost of typically lower conversion efficiency; so composite and multilayer designs are frequently suggested to

combine mechanical strength with useful electrical power [7].

The piezoelectric devices will generally produce alternating and irregular voltage since the mechanical load applied will change with time. Thus, the raw output cannot typically be used directly to power emergency devices and needs to be processed by rectification, voltage regulation, storage of energy in forms other than electrical and control of loads circuits before it can be practically used [8].

3. FOOTSTEP BASED PIEZOELECTRIC FLOOR SYSTEM ARCHITECTURE

A piezoelectric harvesting system based on footstep has generally become a common system which consists of four major subsystems: a mechanical floor structure, piezoelectric transducers, power conditioning electronics and an energy storage or load interface. These subsystems should also be interconnected with other safety devices like LED guidance systems, alarms, sensors, communication modules among others in an emergency application [9].

The mechanical structure oversees transferring human foot pressure to the piezoelectric element as well as ensuring that the piezoelectric element is not exposed to undue stress and long-term mechanical damage. Typical techniques are cantilever beam, bridge type transducer, cymbal structure, stacked plates, disk transducer, spring assisted tiles, and lever types which increase the strain until it reaches the active material [10]. The most common types of piezoelectric transducers that are commonly picked as prototype footstep systems are disk types which are cheap, small and can be easily arranged under floor tiles. Nevertheless, disk transducers are not necessarily the most suitable when it comes to offering the best durability and output with distributed foot pressure unless the tile structure is designed to concentrate and distribute stress effectively [11]. Arrangements of bridge and stack transducers have been the focus of attention as they can enhance the distribution of mechanical stress and conversion of mechanical energy under compressive loading. As can be seen in pavement studies, bridge-type structures can provide good mechanical compatibility and energy conversion efficiency that is applicable to floor tiles that must undergo repeated loading in buildings of the populace [12].

There can be several piezoelectric elements inside a practical emergency floor tile that can be connected in series, parallel or hybrid networks. The series connections add voltage, and the parallel connections add current and the hybrid connection helps to balance the voltage-current requirement of the storage circuit and emergency load [13].

3.1 Design set up and Comparative features.

Table 1. Design set up and Comparative features

Configuration	Primary Strength	Primary Weakness	Appropriate Application
Cantilever beam	High strain under bending	Sensitive to resonance and fatigue	Floor or stair structures containing a lot of

			vibrations
Disk transducer array	Inexpensive and can be installed easily	Low current and concentration risk of stresses plate	prototiles and low-cost pedestrian floors
Bridge transducer	Good compressive load transfer	Needs careful packaging	Modules based on floor tiles and pavement.
Multilayer stack	Increased capacitance and stress distribution	Increased cost and fragility	Higher loads pedestrian areas.
PVDF flexible layer	Durability and flexibility	Less power density than PZT	Flexible mats and wearable-floor systems with flexibility

The type of emergency loading, type of maintenance needed, cost target, and the type of pedestrian density are some of the factors that affect the choice of a given design. A series of ceramic arrays, series-connected, and designed to operate at higher voltages, may be of benefit to a high-voltage LED indicator, but is unnecessary in wireless sensor nodes and alarm circuits that need more reliable regulated DC voltage [14].

4. POWER CONDITIONING AND ENERGY STORING

The output of a piezoelectric harvester typically is an irregular AC signal with high voltage and low current. As emergency lighting, wireless sensors, microcontrollers, buzzers and communication modules all need stable DC power, the power conditioning step is necessary to convert the energy that has been harvested into usable form [15].

The most basic type of conditioning is the full-wave bridge rectifier, which converts AC output to pulsating DC. Nonetheless, traditional diode bridge rectifiers add voltage drops which may cause a serious loss of useful harvested energy, particularly when the piezoelectric source can generate limited current. Further developments Advanced interfaces which may include synchronous rectifiers, active rectifiers, synchronized switch harvesting on inductor (SSHI), bias-flip circuits may be used to enhance energy extraction, reduction of electrical losses, and charge transfer. The circuits are specifically crucial in footstep harvesters since each step generates a short burst of energy that needs to be effectively harnessed [16].

Impedance matching and maximum power point tracking (MPPT) are also of importance since optimum load condition varies based on the footstep force, walking speed, stiffness of tiles and the arrangement of transducers. Adaptive circuits can adjust the effective electrical load to enhance the transfer of power under changing pedestrian activity [17].

Footstep excitation requires energy storage since it is intermittent and emergency equipment needs to be continuously operated. Supercapacitors are appropriate in situations where quick charge-

discharge cycles and short bursts of power are required, and rechargeable batteries are preferred in situations where higher energy density is needed (longer run-time), and long bursts of power are required (high power).

In the case of emergency systems, load priority should be taken into consideration when designing the storage architecture. As an example, the floor-level LED-based guidance can work straight out of a supercapacitor bank during the evacuation process, whereas safety sensors that are wireless may require a controlled low-voltage rail and battery backup to provide continuous monitoring before and after the event [18].

5. EXPERIMENTAL FINDING AND PERFORMANCE TREND

Piezoelectric harvesting footwear has been demonstrated to demonstrate that human walking can supply useful yet limited electrical energy to wearable and low-power electronic devices. Proof of the viability of parasitic power harvesting of walking was demonstrated by early shoe-mounted systems.

The pavement-based studies offer valuable insights to footstep floor system since the two applications share common ground in repeated mechanical loading, protective wrappings and incorporation into infrastructure. Experiments on compression based piezoelectric harvesters have shown that remote transportation equipment and sensors can be powered by these harvesters when placed in appropriate high load locations [19].

There are wide variations in reported outputs due to the variation in material, geometry, loading force, excitation frequency, packaging, electrical load and method of measuring. The transducer configurations that can generate high open-circuit voltages, however, have available current and net stored energy that is often much lower after rectification and regulation losses.

The review of experimental literature indicates that the design of the system level has much more significance than the choice of transducer on its own. The optimization of mechanical amplification, stress distribution, matching electrical impedance, and the low-loss conditioning must be optimized to generate useful energy to be used in emergency applications [20].

In the case of footstep-based emergency systems, reliable support at low-power levels is the realistic target of the safety functions of these emergency systems. Occupancy sensors and LED path markers, intermittent buzzers, low-duty-cycle wireless nodes, and occupancy sensors are more suitable loads compared to high power appliances or full building lighting systems [21].

6. CURRENT APPLICATIONS, ADVANTAGES, AND CHALLENGES OF PIEZOELECTRIC EMERGENCY POWER SYSTEMS

Since the energy harvesting from human footstep can produce electrical energy directly during evacuation, disaster or power failure, piezoelectric energy harvesting has become one of the promising technologies for emergency power applications. In present applications, the main use of LED is to power low energy applications like LED exit signs, floor guiding lights, warning alarms, wireless sensor nodes, smart buildings and transportation infrastructures' occupancy monitoring [22].

In high foot traffic areas such as tunnels, pedestrian bridges, staircases, corridors, and walking trails, as well as underground stations and airports, the use of piezoelectric floor tiles can generate localized power in the event of a grid failure. Some of the benefits of such systems are that they efficiently harness human mechanical energy as a renewable and sustainable power source without using external power sources, and they also simplify wiring and maintenance tasks when combined with internet of things (IoT) based monitoring systems. Furthermore, LEDs need relatively low power to be operated, making them an ideal choice for use in an emergency lighting system that is powered by a piezoelectric mechanism. In practical implementation, however, there are several research gaps and limitations [23].

This generated electrical power is relatively low and highly dependent on the number of pedestrians, walking speed and the force exerted on the floor tiles. Energy losses in rectification, voltage regulation and storage also contribute to a reduction in the actual power. Moreover, the mechanical durability over time, the high installation cost and scalability issues represent challenges for large-scale deployment. Thus, there is a key current research interest to improve energy conversion efficiency, raise the durability of materials, optimize the power conditioning circuits and design hybrid energy harvest systems for effective emergency power applications [24].

7. CHALLENGES AND LIMITATIONS

The main drawback of the piezoelectric harvesting based on footsteps is the low net power output. Though piezoelectric elements can be used to produce large voltages under the impact or compression, their current output is generally low, and much of the energy can be lost during the rectification, voltage regulation, and storage. Another critical challenge is mechanical durability, as the floor tiles should not crack, delaminate, allow water to enter or crack, or their electrical performance to be adversely affected by millions of loading cycles. Ceramic materials that are brittle in nature need to be carefully packed, loads divided, and mechanical stops to ensure that such materials are not damaged under excessive loads [25].

Walking in human beings generates the mechanical excitation which is highly varied. The stress distribution and energy production depends on body weight, walking speed, type of shoes, walking pattern, placement of feet and the density of the crowd making it hard to ensure that power is always generated.

Conditions of the environment like temperature, humidity, dust, water exposure and cleaning processes of floors can worsen the performance of transducers and circuit reliability. Practical systems must therefore have protective encapsulation, moisture proofing, electrical insulation and systems designed to have a high degree of modularity [26].

Issues that have not been addressed yet are economic feasibility and scalability. Piezoelectric floor systems should be cost-effective in comparison with batteries, wired emergency lights and solar-assisted systems as well as traditional backup power; thus, installation is most reasonable in the case of specific places of high traffic or safety-critical situations as opposed to entire buildings [27].

8. OPTIMIZATION STRATEGIES TO BE USED IN PRACTICE

The mechanical optimization must aim at maximizing the useful strain but not to damage the piezoelectric material. This may be done using compliant mechanisms, springs, levers, bridge structures, multilayer stacks and stress concentrators which can convert distributed foot pressure into controlled deformation of the active elements

The electrical optimization must aim at minimizing the losses in conversion and equalizing the output of the transducer to the storage medium and load. Significant methods to enhance net harvested energy are low-loss rectifiers, synchronous switching circuits, DC-DC converters, MPPT algorithms and adaptive impedance matching [28].

The tile placement, pedestrian flow patterns, emergency route patterns, storage capacity, load priority, and access to maintenance should be considered in the system level optimization. The installation of harvesters in the high-footfall areas of entrances, corridors, stairs and exit paths can enhance energy return and minimize cost

Before actual use in real life, reliability testing is necessary. Cyclic loading, impact testing, exposure to moisture, thermal cycling, electrical insulation testing, and full-system energy balance testing should be considered as a part of laboratory tests under realistic pedestrian loading conditions.

9. FUTURE RESEARCH DIRECTIONS

Further studies are to be done on the advanced materials such as ZnO nanowires, lead-free piezoelectric materials based on BaTiO₃, graphene-enhanced composites, PVDF-based flexible films and biodegradable piezoelectric materials. These materials can enhance flexibility, environmental friendliness, and long-term sustainability and can retain useful energy conversion performance.

Another direction of promising directions is hybrid energy harvesting. By incorporating piezoelectric tiles with photovoltaic panels, electromagnetic harvesters, or triboelectric generators can reduce the intermittency of footstep-only systems and will provide a more reliable energy supply to emergency devices [29].

Smart power management will gain even greater significance as systems evolve depending on prototypes to infrastructure deployment. Circuits of the future must support the adaptive load matching, predictive energy budgeting, wireless data transmission, health monitoring, and automatic prioritization of emergency loads.

Digital connection of piezoelectric floor tiles not only as generators but also as functional safety nodes can be made possible. These systems can simultaneously be used to generate energy, identify pedestrian traffic, determine crowd flows, observe structural response, and activate emergency guidance responses [30].

More techno-economic and life-cycle analysis is required to determine the most viable places to find piezoelectric emergency floor systems. Future work needs to compare the installation cost, maintenance needs, carbon effect, reliability as well as safety advantage over conventional batteries, wired emergency lighting and hybrid renewable backup systems [31].

10. CONCLUSION

The piezoelectric energy harvesting systems based on footsteps are new and eco-friendly solutions for transforming mechanical energy produced by humans into electrical energy. Such systems can produce micro-scale power in locations characterized by large density of traffic including transportation hubs, shopping malls and government buildings.

This review has discussed the working principle of piezoelectric materials, system design approaches, power conditioning methods and emergency power usage. Even though the current systems produce relatively small quantities of energy, progress in materials science, power electronics, and smart infrastructure technologies is still aimed at enhancing system performance. As technology advances, piezoelectric floors can be trusted as a power source in the form of an emergency lighting system, safety alarm, and intelligent building infrastructure. Further studies will enable the optimization of efficiency, cost-cutting, and an increase in the practical field of the promising technology.

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