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# Hybrid vibration and wind energy harvesting using combined piezoelectric and electromagnetic conversion for bridge health monitoring applications

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ABSTRACT

In this paper a novel multimodal hybrid bridge energy harvester (HBEH) using combined piezoelectric and electromagnetic conversion is reported. The architecture, fabrication, and characterization of the harvester is discussed. The devised HBEH consists of a permanent magnet, a wound coil, a piezoelectric plate, an airfoil, and two cantilever beams attached to a base support frame. The upper cantilever is holding a permanent magnet and an airfoil as tip mass. A piezoelectric plate is bonded on this beam near its fixed end. On the other hand, the lower beam holds a wound coil. The coil is adjusted in such a way that it is in-line and close to the permanent magnet. The harvester is capable of converting bridge vibrations and ambient wind energy into useful electrical energy to operate wireless sensor nodes (WSNs) for the health monitoring of bridges. Experimentally, the HBEH operated at three, low frequency resonant modes, ranging from 11 to 45 Hz, concentrated around 11, 38 and 43 Hz. Moreover, under sinusoidal base acceleration of 0.6 g, the harvester produced a maximum power of 2214.32 μW across a matching impedance of 28 Ω from its electromagnetic portion at 1st resonance (11.1 Hz). However, a peak power of 155.7 μW was generated by the harvester from its piezoelectric part under 0.4 g base excitation across 130 kΩ load resistance. Furthermore, at 6 m/s pulsating wind speed, the harvester generated load voltages of 25 mV and 114 mV from its electromagnetic and piezoelectric portions when connected to optimum load impedance of 28 Ω and 130 kΩ respectively.

## 1. Introduction

Monitoring the structural health of critical infrastructures and civil entities such as tall buildings, bridges, flyovers and underpasses sets forth to get rid of catastrophic failure, subsequent human casualties and to avoid traffic delays [1]. Health monitoring increases safety, reliability and quantifies real time damage detection. In addition, it helps in timely repairing to reduce the maintenance cost. For this purpose, wireless sensor nodes (WSNs) are deployed in critical structures to continuously and remotely interrogate their condition [2] (see Fig. 1).

In WSN, a sensor detects the physical and environmental condition which is manipulated and transmitted by signal conditioning circuit for processing to a microcontroller. Data and configurations are stored in memory and a wireless transceiver receives and transmits data to a base station. Battery is usually a power source for each sensor node. A challenging limitation for continuous operation of WSNs is the non-stop power supply (see. Table 1).

However, the battery installed in a WSN is unable to supply power for long duration of time due to its short life span. This actually limits the applications of WSNs in remote, hazardous and embedded systems, where frequent battery changeover is not possible. On bridge and flyover structures, the available ambient energies include solar, acoustic, vibration and wind energy. Mechanical vibrations can be harvested to power electronic devices, such as autonomous WSNs, wearable electronics, ultra-low power microelectronic devices and portable gadegts in bio-medical applications [3–5]. Efforts have been made to develop vibration energy harvesters (VEHs) based on conversion mechanisms, like, piezoelectric [6–8], electromagnetic [9–11], acoustic [12,13], and wind [14,15], either to prolong the life span of the battery installed or then to eradicate it. Piezoelectric and electrostatic energy harvesters (EEHs) are best fitted to micro-electromechanical system (MEMS) applications because of low power output (due to their higher internal impedance) [16]. However, electromagnetic energy harvesters (EMEHs) are suited for large power requirements [17]. An energy harvester developed in [18] is integrated with a WSN that can transmit information to the remote location after every 3 min and harvester

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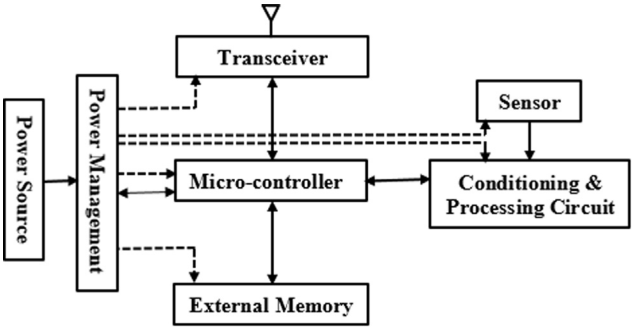

**Fig. 1.** Block diagram of a wireless sensor node.

**Table 1**
Power consumption of ultra low power sensors.

| Sensor type | Minimum voltage (V) | Minimum current (μA) | Power (μW) |
|---|---|---|---|
| Pressure | 1.8–2.1 | 1–4 | 1.8–8.4 |
| Temperature | 2.1–2.7 | 0.9–14 | 1.89–37.8 |
| Acceleration | 1.8–2.5 | 10–180 | 21.6–324 |

**Table 2**
Bridge's vibration data.

| Bridge name and location | Frequency (Hz) | Acceleration (g) | Ref |
|---|---|---|---|
| Pershagen bridge (Sweden) | 3–50 | 1.2 | [4] |
| Vehicle-bridge (China) | 16–33 | 1 | [7] |
| Seohae grand (South Korea) | 1 | 0.02 | [18] |
| IH-35N over Medina River (Texas) | 3.1 | 0.15 | [19] |
| Ferrite (Sweden) | 4.1 | 0.02 | [24] |
| Komtur (Berlin) | 2–2.6 | 0–0.0061 | [25] |
| Seohae Grand Bridge (S. Korea) | 1 | 0.0125 | [26] |
| NC (USA) | 1–40 | 0.01–0.1 | [30] |
| North (France) | 0–50 | 0.85 | [33] |
| Ypsilanti (Michigan, USA) | 2–30 | 0.01–0.035 | [45] |
| Pershagen Bridge (Sweden) | 7.8 | 0.162–0.197 | [46] |
| RT11 (New York, USA) | 1 | 0.55 | [47] |
| Grove Street (Michigan, USA) | 2–30 | 0.01–0.05 | [48] |
| New Arsta (Sweden) | 1–40 | 0.01–3.79 | [49] |
| Harvard Bridge (Boston, MA), USA | 8.3–17.2 | 0.35 | [50] |
| New Carquinez (California, USA) | 2 | 0.055 | [51] |
| Slab-on-girder FHWA, (USA) | $> 10$ | 0.47 | [52] |
| Huanghe Cable-Stayed Bridge (China) | 1–2 | 0.015 | [53] |
| Ferrite (Sweden) | 14–15 | 0.02 | [54] |
| Golden Gate (Francisco, USA) | 0–1.5 | 0–0.061 | [55] |
| California, USA) | 10–20 | 0.0002 | [56] |
| Box grider (Austin, USA) | 1–15 | 0.12 | [57] |
| Komtur (Berlin, Germany) | 2–2.6 | 0–0.006 | [58] |
| New Arsta (Sweden) | 1–5 | 0.3–1.5 | [59] |

produced a targeted power at low frequency and excitation level of 0.02 g. A vibration based EMEH for powering wireless acceleration sensor node (WASN) is reported by R Torah et al. [19]. The micro ($150\ \text{mm}^3$) energy harvester produced an output power of 58 μW at 52 Hz and under 0.06 g base acceleration. Conventional VEHs are generally single resonant state with high resonance [20], and if there is a shift in the operating frequency, it's performance degrades dramatically [21]. Most of the practical vibrating structures are time varying and exhibit random vibrations of low frequency and wide bandwidth [22], therefore, low frequency vibrations is a topic of prime importance for researches to scavenge energy.

Bridges exhibit non-periodic, low frequency and low amplitude traffic-induced vibrations. These vibrations are quite enough for the installed energy harvesters over a bridge to power wireless sensor/s [23] for lasting, non-stop energy supply. Work has been done for structural health monitoring of bridges utilizing bridge's vibrations and ambient wind, including an electromagnetic-type bridge energy harvester (EMBEH) comprised of wound coils and multilayer magnets (increased magnetic flux density between poles) [24]. At an input frequency of 4.1 Hz and 0.02 g base acceleration, the reported harvester delivered a maximum power of 3.43 mW to a load resistance of 145 Ω. A low-cost temperature resistant and waterproof, 3-axis bridge condition monitoring WASN is developed by [25]. The wireless sensor node can continuously monitor and record data using bridge's vibrations as power source. An EMBEH that can harvest traffic-induced bridge vibrations is repoted in [26]. The fabricated harvester can generate electrical power of 2 μW at a frequency range of 1–4 Hz. For condition monitoring of bridges and to make the WSNs autonomous, the designed EMBEH in [27] produced a peak power of 57 μW and average power of 2.3 μW, harvesting non-periodic bridge vibrations of an input frequency of 2 Hz and 0.05 g harmonic excitations. For the vibrations monitoring of Voigt bridge [28], a wireless sensor network containing 20 wireless sensing units encapsulating in a plastic container of $265.2\ \text{cm}^3$ is installed over the bridge. Each sensing unit collects and communicates information with a network server and is comprised of three modules; an analog to digital converter (ADC), a computational, and a communication module. The ADC component can support frequency sampling of up to 100 kHz, with an output voltage range from 0 to 5 V. The extent and location of damage in bridges was predicted from structural vibration signature (SVS), by installing a number of WASs [29]. To help in footbridge's design, Kala et al. [30] used pedestrian load-induced forces information to measure the frequency 1.3–2.3 Hz and acceleration 0.01–0.08 g range at a specific footbridge in Kolin (Czech Republic, Europe). To harvest the wide-range, low frequency bridge's vibrations, a multi resonant EMBEH using traffic-induced bridge's vibrations and ambient wind is proposed in [31]. The harvester practically exhibit three resonant modes of 3.6, 14.9 and 17.6 Hz. When excited at 3.6 Hz, an average power of 354 μW was delivered to a matching impedance of 54.5 Ω under an excitation amplitude of 0.4 g. A multimodal EMBEH with three fundamental frequencies of 7.6, 33 and 45 Hz is reported by [32]. The harvester generated a maximum power of 1955 μW at first resonance and under 0.6 g base acceleration. Bridge's vibration informations are summerised in Table 2. The range of base excitation and frequecy of excitation levels is different at various bridges, and can be concluded that, bridges vibrate in a frequency range of 1–50 Hz and base excitaion level of 0.01–3.79 g [33].

Hybrid (piezoelectric-electromagnetic) energy harvesting technology has been introduced by researchers recently due to multi resonant frequencies and wide operating bandwidth that resulted in more power producing capabilities as a result of dual transduction mechanism [34,35]. Challa et al. [36] developed a cantilever beam type hybrid energy harvester which produced about 30% increased power as compare to the stand alone piezoelectric or electromagnetic module. Yan et al. [37] overwhelmed the narrowband operating frequency challenge of the harvester by introducing a two-degree-of-freedom (2 DOF) hybrid energy harvester. Toyabur et al. [38] represented a multimodal hybrid energy harvester with resonant frequencies of 12, 15, 17 and 22 Hz. The reported harvester produced 250.23 μW power across 90 KΩ optimum load and 244.17 μW across 10 Ω at 3rd resonance and under 0.4 g acceleration from piezoelectric and electromagnetic generators respectively.

In this work, a multimodal HBEH has been proposed to overcome limitations of the previous reported bridge energy harvesters (BEHs) and to harvest low frequency bridge's vibrations with increased operation bandwidth. A novel hybrid system with capability of converting both low frequency bridges' vibrations and ambient wind simultaneously into useful electrical power is developed. The devised harvester is using combined piezoelectric and electromagnetic transformation, rather than the stand-alone electromagnetic or piezoelectric energy harvesting technique. Organization of the paper is as follows: proposed design and working principle is explained in Section 2. In Section 3, the system is modelled as lumped parameter model, and power equations are derived. Prototype fabrication and experimental setup is described