EFFICACIOUS PIEZOELECTRIC ENERGY HARVESTING
INCLUDING STORAGE FROM LOW-FREQUENCY NON-PERIODIC
BRIDGE VIBRATIONS

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Abstract:

Although piezoelectric energy harvesting (PEH) from structural vibrations is well-recognized as a viable paradigm for renewable power generation in micro to milli watt range, most real-life structures, such as bridges, are characterized by low-frequency erratic vibrations, which tend to diminish their practical utility for PEH. This is because the interface circuits involved in rectification and storage tend to lose their efficiency on account of low-frequencies and erratic nature of real-life structural vibrations. This paper proposes a fine-tuned D1000 bridge rectifier circuit to circumvent the problem, culminating in a successful proof-of-concept demonstration of PEH and subsequent storage in Ni-MH rechargeable batteries from real-life bridge vibrations. The unique feature of the experimental study entails successfully utilizing simple type piezo elements directly bonded on the host structure and operating in $d_{31}$ mode. Additionally, piezo elements bonded on a secondary cantilever structure acting as a parasite to the main structure are also studied for comparison. The first part of the paper presents laboratory-based experimental investigations of the bridge rectifier circuit for charging a battery from the energy harvested using piezoelectric
Results show that it is feasible to charge a battery under low-frequency and small voltage scenario ($V_{oc} = 1$ V at 5 Hz) by employing the proposed D1000 rectifier circuit. Next part presents field evaluation of the fine-tuned circuit on vibrations of real-life flyover. Storage of energy in capacitor as well as battery is successfully realized in realistic environment, achieving a power of 0.27 mW. The study represents successfully raising the technology readiness level (TRL) of PEH from structural vibrations to level 7.

**Keywords:** Bridge, Vibrations, Piezoelectric energy harvesting (PEH), Rectifier circuit, Battery storage, PZT, Low-frequency vibrations.

### 1. INTRODUCTION

Wireless sensor nodes (WSNs) deployed for internet of things (IoT) are powered by onboard batteries which have finite lifespan, thus limiting the functionalities of wireless sensing systems for applications in various sectors such as industry, military, civil- infrastructures and other systems\(^1\).\(^2\). Replacement or recharging of batteries can be inconvenient and sometimes infeasible in remote hazardous locations. The power requirements of commercial ultra-low power WSNs employed for structural health monitoring (SHM) and data transmission is in the range of 3-18 mW. Harvesting renewable energy is one of the most essential technologies to realize true self-sustainable SHM by providing an alternate power source to the WSNs. The theoretical concept of piezoelectricity is well-known in the literature. In simplest terms, when a piezoelectric patch is squeezed or elongated (i.e., mechanically strained), an electric charge accumulates at the electrodes. This is called the ‘direct piezoelectric effect’. The relation between the voltage generated across the PZT patch and strain can be expressed as\(^3\)
\[ V = \left( \frac{d_{31}Y^E R}{\varepsilon_{33}^T} \right) S_1 \] (1)

where \( d_{31} \) is the piezoelectric strain coefficient, referring to Figure 1, \( S_1 \) is the mechanical strain (along axis 1) and the electric field \( E_3 \) (along axis 3). Further, \( \varepsilon_{33}^T = \varepsilon_{33}^T (1 - \delta j) \) the complex electric permittivity (along axis ‘3’) under constant stress, with \( j = \sqrt{-1} \), and \( \eta \) and \( \delta \) respectively denoting the mechanical loss and the dielectric loss factors of the piezoelectric material. \( Y^E = Y^E (1 + \eta) \) is the complex Young’s modulus of elasticity of the piezoelectric material.

Harvesters based on piezoelectric energy harvesting (PEH) are becoming popular because of the ease of scaling, high power density and relatively high output voltage in comparison to the electromagnetic and the electro-static systems\(^4\). In civil-structures, such as city flyovers, vibration energy is abundantly available and can be utilized for energy harvesting using piezoelectric materials, which can directly convert mechanical strains to voltage signals without involving complex geometries or moving components. They are, however, characterized by non-periodic and low-frequency vibrations, often erratic in nature, rendering the efficiency of most diode and metal-oxide semiconductor field effect transistor (MOSFET) circuits to as low as 12\(^%\)\(^5\).

Several studies have been reported on energy harvesting from bridges- both steel and reinforced concrete (RC). Williams et al.\(^6\) measured vibration data from bridges and applied the same as excitation source to a theoretical model based on an inductive generator to estimate the output power. Durou et al.\(^7\) explored combined vibration and thermal energy harvesting, storing the generated electrical energy in a supercapacitor for powering SHM sensors on aircraft. It was
concluded that vibration harvesting alone was not suitable to power the SHM node, but it has potential to supplement the solar harvesting system for not being dependent on daytime. A wireless SHM system based on PEH was developed by Zhou et al.\textsuperscript{8}. The sensor node used a cantilever based piezoelectric device to harvest vibration energy and a microcontroller device to perform impedance-based SHM. However, when experimentally tested, the energy harvesting system could not generate enough power to run the SHM device. Kim et al.\textsuperscript{9} conducted an experiment using unimorph piezoelectric cantilever for energy harvesting. The piezoelectric module could generate about 13.8 V under cyclic loading of 10 kN. Ali et al.\textsuperscript{10} theoretically estimated the possibility of power generation using a cantilever setup for PEH. The results show that the presence of mass decreased the output. However, real device development and experimentation were not performed. Peigney and Siegert\textsuperscript{11} explored energy harvesting from traffic-induced bridge vibrations using a cantilever bimorph consisting of a tip mass and two Mide QP20W piezoelectric patches bonded to the clamped end of a steel plate. The cantilever was not directly bonded on the girder of the bridge but installed on some pipe fixed on the girder. The theoretical output power was predicted in terms of traffic-intensity though a simple model, followed by experimental verification. Results showed that a power of 30 µW was achieved at frequency of 14.5 Hz. Kaur and Bhalla\textsuperscript{3} demonstrated the feasibility of combined SHM and PEH from the thin PZT patches in the form of concrete vibration sensor (CVS) for RC structures. The power generated by the patch was determined as 1.417 µW. Iqbal et al.\textsuperscript{12} developed a hybrid energy harvester by the combination of piezoelectric and electromagnetic systems. It comprised of two cantilevers: the upper cantilever with a permanent magnet, and the lower one holding a wound coil. Laboratory experimental results showed achieving a power of 2.214 mW across a 28 Ω at 0.6 g and 155.7 µW across 130 kΩ under 0.4 g. Wang et. al., proposed a generator for PEH
from the suspension structures. The energy was collected through the bending patterns of the piezoelectric layers. The output peak power of 1.7 mW was achieved at a force loading of 120 g$^{13}$. A very important component of a PEH system is the interface circuit, which is usually deployed at the output of the piezo element in order to convert the voltage signal from alternating current (AC) to direct current (DC) and to optimize the electric output power. Several types of electronic interface circuits have been proposed for this purpose. The first attempt was made by Ottman et al.$^{14}$ who used the concept of impedance matching and implemented an adaptive control technique to design an interfacing circuit. The circuit composed of an AC-DC rectifier and a DC-DC step-down converter operating in discontinuous conduction mode (DCM). The converter performed better at excitations producing voltages of 25 V or higher in the piezoelectric element as compared to lower voltages. A variety of switch interface circuits have also been proposed in the literature. Guyomar et al.$^{15-16}$ proposed first a nonlinear technique named synchronized switch harvesting on inductor (SSHI), which worked better for weakly coupled PEH systems$^{17-18}$. The implementation of these elements involved complex circuitry and components for signal detection, switch operation, inductors, and optimal load. Also, a displacement sensor and a controller was needed for synchronization and generation of the switching commands$^{19-21}$, which however consumed higher power than the harvestable power, thus rendering them in infeasible for practical deployment. Lallart et al.$^{22}$ derived a rectifier from S-SSHI and SECE technique, known as a double synchronized switch harvesting (DSSH). The advantage of DSSH is that by tuning the ratio between the piezoelectric capacitor and the intermediate capacitor, the trade-off between the damping effects and the harvested energy could be controlled. Further improvement of the DSSH technique by Shen et al.$^{23}$ led to the concept of enhanced synchronized switch harvesting (ESSH).
The ESSH technique exhibited a lower sensitivity to mismatch in the capacitance ratio and also provided a finer control on the harvested energy. Kashiwao et al.\textsuperscript{24} compared the bridge and the double-voltage rectifier circuits for a vibration energy harvesting system using macro-fiber composite (MFC) based piezo patches. The experimental results showed the power efficiency of the bridge circuit to be higher than that of the double-voltage rectifier circuit; however, the bridge circuit was found suitable at a low voltage only.

Past research work undertaken on PEH have considered secondary structures such as cantilever beams for harvesting energy. The main focus of past studies was either on the improvement of the configurations of the secondary cantilever structure or of the electronic interface circuits to scavenge maximum power from the generator\textsuperscript{25}. Yet, a notable disconnect appears in the knowledge on the effective electronic interface circuits and use of piezoelectric element directly bonded to the host structure undergoing non-periodic (and often erratic) vibrations at very low-frequencies (less than 5 Hz) for self-sustainable SHM applications. Roach and Neidigk\textsuperscript{26} have classified the technology maturity level on a 9-point scale (see Table 1) termed as technology readiness level (TRL). Currently, PEH for SHM is placed at level 4. As per TRL scale, piezoelectric materials have been widely explored on lab-sized structures over the last few decades, but their potential on real-life civil-structures has not been fully understood as well as demonstrated on real-life environment and therefore not visible yet at commercial level. In this paper, this aspect of PEH is addressed at practical level on real-life structures.

This paper presents laboratory and field experimentation using a fine-tuned bridge rectifier circuit to demonstrate the feasibility of charging a rechargeable battery from the vibrations of a real-life
city flyover using piezoelectric element bonded directly on the girder. In such real-life structures, the signals are erratic in nature and are characterized by low frequencies (<5 Hz) and low voltage amplitudes (1-2 V). The proof-of-concept experimental demonstration presented in the paper represents a rise in TRL from 4 to 7, which the main contribution of the paper. The structure of paper is as follows. The next section covers the laboratory experiment involving the proposed circuit elements. This is followed by field experiment which includes charging of battery first through a piezoelectric cantilever harvester (PCH), and then from the piezo patches directly bonded to the host vibrating structure, a steel girder city flyover. The succeeding section is on experimental results and discussion, finally culminating in conclusions.

2. LABORATORY PARAMETRIC INVESTIGATIONS

This section covers benchmark laboratory experimental investigations for fine-tuning storage of energy generated from the vibration of piezoelectric elements (in simple $d_{31}$ configuration) in a rechargeable battery and the related parametric studies. Previous experimental study was conducted by authors using capacitors. A rechargeable battery is superior to a capacitor since it ensures long term power retention. Towards this end, experiments were conducted in laboratory, simulating real-life conditions of frequency and voltage. Recently, the authors conducted an elaborate study involving diode based rectifier circuit (DBRC), MOSFET based rectifier circuits (MBRC), Gate cross-coupled rectifier (GCMOS) and Full Gate Cross-Coupled MOSFET Rectifier circuit (FGMOS). The experiments were performed to harvest energy from an MFC piezo patch bonded on cantilever beam which was subjected to various vibrational frequencies (5 Hz, 7 Hz, 9 Hz, 11 Hz, 13 Hz, and 15 Hz) and voltage amplitude (1 V, 2 V, 3 V, and 4 V) generally available in civil structures. Input signals were non-sinusoidal resembling real-life scenarios.
Experimental results showed that the best performance by D1000, a diode-based rectifier circuit, under all combinations of frequencies (5-15 Hz) and voltages (1-4 V) which are generally found in civil structures. Table 2 reproduces the efficiency demonstrated by various interface circuits. Charging efficiency of about 81.33% and harvestable power of 29.48 nW was achieved for 1 V open-circuit piezoelectric voltage at 5 Hz in case of D1000 circuit.

D1000 is a diode-based rectifier circuit comprising of Schottky-type diodes, model BAT1000\textsuperscript{29}. BAT1000 diodes is characterized by a lower forward bias voltage of around 0.2 V. The forward voltage ($V_f$) can directly affect the output efficiency of the rectifier circuits. The topology consists of a bridge rectifier with an energy storage capacitor and the piezoelectric voltage source at the input, as shown in Figure 2. This is the simplest topology reported in the literature\textsuperscript{30}. The four diodes labelled, $D_1$ to $D_4$, are arranged in “series pairs” with only two diodes conducting current during each half-cycle when the applied input voltage ($V_{ac}$) is greater than the diode threshold voltage ($V_{th}$). During the positive half-cycle of supply, the diodes $D_1$ and $D_4$ conduct in series, while the diodes $D_2$ and $D_3$ are reverse biased, hence switched off. On the other hand, during the negative half-cycle, the diodes $D_3$ and $D_4$ conduct in series while the diodes $D_1$ and $D_2$ switch “OFF” as they are now reversed biased. Utilizing a bridge rectifier is advantageous because it creates entirely passive circuit systems. The same has been employed in the present study by replacing the capacitor by a rechargeable battery.
2.1 Laboratory battery charging study

Figure 3 shows the laboratory experimental setup to evaluate the performance of D1000 rectifier circuit for charging a rechargeable battery. The setup consisted of an amplifier unit and a miniature shaker to excite the a glass fibre composite cantilever beam (220 × 35 × 1 mm in size) provided by the manufacturer on the root of which the MFC patch of size 85 × 28 ×0.3 mm\(^3\) was bonded to harvest the vibration energy on (see Tables 4 and 5 for details). To ensure charging and storing of the energy in the battery and for better evaluation of the optimized circuit, low (1 V), as well as high (4 V) input voltage amplitude and frequency (5 Hz and 10 Hz) scenarios, were considered and same were generated using the desktop shaker and the composite beam. The setup was employed to generate the voltages and the frequencies closely matching the vibrations of the real-life flyover\(^{27}\). The D1000 rectifier circuit was connected to the output of the MFC patch, and a nickel-metal hydride (Ni-MH) rechargeable battery of 15 mAh\(^{32}\) was connected at the output of the rectifier circuit (see zoomed position of Figure 3) and allowed to charge to its full potential. Ni-MH battery was chosen because it has a high charge density as compared to the lithium ion battery and does not require any type of charge controller or voltage regulator. Keysight 34411A digital multimeter (DMM) was used to measure the voltage signals generated across the battery and the charging time was recorded using the Intulink software which operated in excel format. Figure 4 shows the open circuit voltage (\(V_{oc}\)) signal captured by the oscilloscope. It can be observed that the waveform has non-sinusoidal components resembling real-life bridge type vibrations, as shown in Figure 5.

The experiment was conducted at high open circuit voltage, \(V_{oc} = 4\) V and low voltage scenarios, \(V_{oc} = 1\) V at frequencies of 5 and 10 Hz to charge the battery. Figure 6 shows the charging curve
of the battery at the two frequencies. It is observed that when the cantilever is excited at 5 Hz and
10 Hz at $V_{oc} = 4 \text{ V}$, the battery is charged to a voltage of 2.52 V in 19728 seconds (5.48 hours) and
3.10 V in 24012 seconds (6.67 hours) respectively. It can also be seen that for $V_{oc} = 1 \text{ V}$, at 5 and
10 Hz frequencies, the battery is charged to the final voltage of 0.88 V in 4320 seconds (1.2 hours)
and 0.93 V in 5544 seconds (1.54 hours), respectively. In general, it can be concluded that as the
excitation frequency and input voltage increase, the voltage across the battery increase. However,
it takes longer to charge as frequency increases.

In order to determine the total energy stored into the battery by means of PEH, it was discharged
by connecting a resistive load across it and monitoring the discharging process. Figure 7 shows
the voltage discharging curve of the battery across a 4.7 kΩ resistor. It can be observed that when
the battery is initially charged to 2.52 V (4 V, 5 Hz) and 3.10 V (4 V, 10 Hz) respectively, it can
power a load of 4.7 kΩ resistor for 32724 seconds (9.09 hours) and 40464 seconds (11.24 hours),
respectively. Similarly, if the battery is charged to 0.88 V (1 V, 10 Hz) and 0.93 V (1 V, 10 Hz)
respectively, it can power a load of 4.7 kΩ resistor for 12240 seconds (3.40 hours) and 15120
seconds (4.20 hours), respectively. The total harvested energy, ($E_h$), as shown in Figures 8 (a), was
determined as the area under the curve of power with respect to time, computed from Figure 7,
using integration of $V^2/R$ function. It can be noted from this Figure that an energy of 19.77 J (10
Hz) and 29.65 J (5 Hz) was harvested for $V_{oc} = 4 \text{ V}$ and 0.65 J (10 Hz) and 0.72 J (5 Hz) for $V_{oc} =
1 \text{ V}$. The average harvested power ($P_{avg}$), as shown in Figure 8 (b), was determined by dividing
the total harvested energy by the total charging time ($T_c$), as

$$P_{avg} = \frac{E_h}{T_c}$$  \hspace{1cm} (2)

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It can be seen from this Figure that a power of 1 mW and 7 mW was achieved for $V_{oc} = 4$ V at 5 Hz and 10 Hz respectively. Similarly, 0.15 mW and 0.18 mW power were achieved for $V_{oc} = 1$ V at 5 Hz and 10 Hz respectively. Experimental results show that it is feasible to charge a battery under low-frequency and small voltage scenario ($V_{oc} = 1$ V at 5 Hz) under non-periodic vibrations by employing optimized D1000 rectifier circuit, harvesting power in milli-watts range.

In the next section the evaluation of the D1000 rectifier circuit is carried out using simple type piezo patch from lab-based wind-induced vibrations, somewhat representing more real-life pattern, for exploring the possibility of storing the energy in rechargeable battery.

3. EXPERIMENTAL SET UP FOR PEH FROM WIND-INDUCED VIBRATIONS

The experimental setup consisted of a lab-sized (1 m long) wind tunnel, a chamber made of acrylic sheets, as shown in Figure 9. One end of the tunnel was open, and the other was fitted with an exhaust fan. The fan speed was controlled using a dimmer switch. A digital anemometer was used to measure the wind velocity. The energy harvesting structure consisted of a pair of aluminium cantilever beams of size 200×35×0.5 mm, joined together by a triangular connector, which served to enhance fluttering of the beam is shown in Figure 10. A PZT patch of size 10×10×0.3 mm, grade PIC 151, was bonded on the fixed side of an aluminium cantilever beam using standard Araldite epoxy adhesive. For detailed materials properties of the PZT patch refer, Table 3. The properties of aluminium cantilever beam are listed in Table 5. The D1000 rectifier circuit was connected to the output of the PZT patch. A Ni-MH rechargeable battery of 15 mAh was connected at the output of the rectifier circuit and allowed to charge to its full potential. The Keysight 34411A
DMM was used to measure the voltage of the battery and the charge time was recorded using an intulink software.

Figures 11 (a) and (b) show the typical open circuit voltage signals captured by the oscilloscope at the minimum speed of 1.6 m/s and the maximum speed of 3.2 m/s of the fan, which correspond to peak open voltage of 1 V and 5 V respectively. The waveform has non-sinusoidal components. The FFT plots can be observed in Figures 12 (a) and (b) at the minimum and the maximum speed of the fan respectively, showing that the frequency of the induced was equal to 4 Hz and 4.4 Hz respectively. Figures 13 (a) and (b) show the charging curve of the battery from the PZT patch bonded on the cantilever corresponding to the minimum and the maximum fan speeds respectively. It can be observed that the battery was charged to the final voltage of 1.93 V in 26532 seconds (7.37 hours) and 0.44 V in 15840 seconds (4.40 hours), respectively, at the maximum and the minimum fan speed. Figures 14 (a) and (b) show the voltage discharging curves of the battery across a 4.7 kΩ resistor. It can be observed that if the battery is charged to 1.93 V and 0.44 V, then it can power a load of 4.7 kΩ resistor for 6.87 hours and 1.25 hours, respectively, when charged at the maximum and the minimum fan speeds. The total harvested energy and average harvested power were determined as 9.64 J and 0.36 µW for maximum fan speed, respectively. The same were 125 mJ and 7.9 µW for the minimum fan speed respectively.

Thus, the charging of the battery was successfully demonstrated from wind induced vibrations by using very simple type PZT patches. Power in micro-watts range was achieved. This study shows the potential of wind induced vibrations available in exteriors as well as interiors (HVAC) for PEH. Next section will carry out the evaluation of the optimized D1000 rectifier circuit in the field.
from the traffic-induced vibrations of real-life city flyover and explore the possibility of storing the energy in the battery.

4. FIELD EXPERIMENT: PEH FROM REAL-LIFE TRAFFIC-INDUCED VIBRATIONS

After successful conduct of laboratory experiments, the field experiment was carried out by considering the ambient vibrations of a real-life city flyover to evaluate the performance of an optimized rectifier circuit by charging a rechargeable in a realistic environment. The battery was charged in two ways, firstly through, a piezoelectric cantilever harvester (PCH) attached to the bridge, and then through piezoelectric patches bonded to the host structure. Both MFC type and simple type PZT patches were considered. The following subsections cover the detail of the field experiment. The field experiments were conducted on the Jia Sarai flyover located in the vicinity of the Indian Institute of Technology Delhi, from which vibration measurements were carried out previously by the author. It is a typical steel girder type flyover with RC deck, as shown in Figure 15. The portion selected for the measurement had girder depth of 2 m and a span of 28 m. In the previous study conducted on the same bridge, direct measurement of voltage and power was not made. Acceleration was measured on real bridge and following equation used to determine strain from acceleration

\[ S_1 = \frac{1.2Da}{\pi^2L^2f^2} \]  

where, \( S_1 \) is the strain, \( D \) the girder depth, \( a \) the measured acceleration, \( L \) the bridge span and \( f \) the frequency. Equation 1 was further used to determine peak voltage if a PZT patch were bonded. In the present study, however, direct measurement of voltage and power has been made from a PZT patch directly bonded on the bridge.
4.1 Installation of Piezo Patches

For the secondary structure mode, a stainless-steel PCH of size 450 x 30 x 1 mm was chosen as a secondary structure. A commercially available MFC patch of size 85×28×0.3 mm, Model M-8528-P2 was bonded on the cantilever using standard Araldite epoxy adhesive, as shown in Figure 16 (a). In order to achieve maximum efficiency, it was tuned to 4 Hz, to match the fundamental frequency of the considered bridge. Figure 16 (b) shows the frequency domain response of the PCH to an impact test measured using the MFC patch. From this, the natural frequency of the PCH is found to be 4 Hz, which is same as the dominant fundamental resonant frequency of the bridge.

Figure 17 shows installation of the PCH underneath the girder with the help of a magnet. It was fixed the mid-point of the exterior girder of the flyover facing IIT side of the road. An open-circuit voltage of 4.5 V (average) was measured to be generated from the MFC patch bonded on the PCH when the bridge was under traffic, as shown in Figure 18, when continuous measurements were made for two hours during the daytime.

In addition to the PCH, a PZT patch of size 10×10×0.3 mm, grade PIC 151 and MFC patch of size 85×28×0.3 mm, Model M-8528-P2, were installed directly on the underside of the girder directly, adjacent to the PCH. Figure 18 shows the installation steps of the PZT patch on the girder. It was bonded on the underside of the girder using standard Araldite epoxy adhesive after cleaning the surface of the girder using a sand paper, covered with a plastic film and then pressed on the beam surface using a strong magnet for proper adherence, as shown in Figures 19 (a) and (b) respectively. In this way, 24 hours of pressure curing was done. The patches were then soldered and covered with epoxy to protect the soldering, as shown in Figures 19 (c) and (d) respectively. In the very first attempt, the PZT patch had broken down due to the high impact of magnet over...
the patch, as shown in Figure 20. The installation of the piezoelectric element was successful after multiple attempts. Figure 21 similarly shows the steps involved in the instrumentation of the MFC patch directly on the girder. The success rate is much higher for MFC patch as compared to the PZT patch.

Figures 22 (a) and (b) show the typical time-domain plots of the open-circuit voltage generated from the PZT and MFC patches, respectively. Peak voltages of 0.74 V and 2.5 V were observed for the PZT patch and the MFC patch respectively. The Fast Fourier transform (FFT) of signals from both the patches, as can be seen in Figure 23 revealed that the dominant fundamental resonant frequency of the bridge was 4 Hz, matching with the previously measured bridge frequency. It can be noted that the open-circuit voltage of 0.74 V generated from the PZT patch closely matches with the estimated open-circuit voltage of 0.78 V based on the measurement of the acceleration in the previous studies\textsuperscript{27}.

4.2 Field Power Measurement

Figure 24 shows the experimental setup for charging a rechargeable battery using an optimized D1000 rectifier circuit from the voltage signals generated from the sensors installed on the bridge. Oscilloscope was used to measure the output signals from the piezo elements. Keysight 34411A DMM was used to measure the voltage across the battery, and the charging time was recorded using the intulink software. A portable generator was used to provide power supply to all the equipment used in the experiment. It was rested on ground sufficiently far from the bridge piers to ensure proper isolation of its vibration. In the field experiments, the PCH was first employed to measure the level of voltage signals from a real-life environment and evaluate the rectifier circuit
by charging a battery. Thereafter, the PZT and the MFC patches directly bonded on the girder were evaluated. The D1000 rectifier circuit was used as interface circuit for both the patches. A Ni-MH rechargeable battery of 15 mAh capacity was then connected at the output of the rectifier circuit (see Figure 24) for charging to its full potential. Details are covered in the following subsections.

4.2.1. PEH from PCH

Figures 25 (a) and (b) show the charging and discharging curves of the battery for the cantilever PCH (Figure 16). It can be observed from Figure 25 (a) that the battery charged to the final voltage of 1.62 V in 26856 seconds (7.46 hours). Figure 25 (b) shows that when charged to 1.62 V, then it can power a load of 4.7 kΩ resistor for 22608 seconds (28 hours). From Figure 25 (b), the total energy stored into the battery during charging was worked out by integration of \( V^2/R \) function with time. This was determined to be 7.46 J. The average harvested power from the PCH \( (P_{avg}) \) of 0.27 mW was determined using Equation (2). From this experiment, it is established that optimized D1000 rectifier circuit can be employed for PEH from real-life bridge vibrations. The next measurement was carried out from the piezo patches (PZT and MFC) directly bonded on the girder.

4.2.2 PEH from Directly Bonded Piezoelectric Patches

Figures 26 (a) and (b) show the charging curve of the battery from the MFC and the PZT patches bonded directly on the girder (Figure 19 and 21). It can be observed that the battery was charged to the final voltage of 1.18 V in 29088 seconds (8.08 hours) and 0.32 V in 17496 seconds (4.86 hours), respectively, by the MFC and the PZT patches. Figures 27 (a) and (b) show the discharging curves of the battery across the 4.7 kΩ resistor for the MFC and the PZT patches. It can be observed that when the battery was charged to 1.18 V and 0.32 V, then it can power a load of 4.7 kΩ resistor
for 16488 seconds (4.58 hours) and 1620 seconds (0.45 hours), respectively, for the MFC and the
PZT patches. The total harvested energy and the average harvested power were determined as 5.13
J and 0.17 mW, and 26 mJ and 1.56 µW, from the MFC and the PZT patches, respectively.
Additionally, an electrolytic capacitor of 1 µF was also charged to 0.6 V from the real-life bridge
vibrations in 370 seconds using PZT patch, as shown in Figure 28. The energy per hour and an
average harvested power of 1.8 µJ and 0.5 nW were respectively obtained.

It can be noted that in field experiment an energy of 26 mJ was accumulated into the battery in
case of PZT patch at a minimum input voltage of 0.74 V and 4 Hz in 4.86 hours [see Figure 27
(b)]. Based on this observation, energy harvesting time required for the one-time operation of some
typical ultra-low power consuming electronic gadgets, such as digital temperature sensor, smoke
detector, impedance analyzer (AD5933) etc., are summarized in Table 6. It can be observed from
the Table 6 that continuous harvesting for 12 minutes from the real-life bridge vibration using PZT
patch is enough for one-time operation of typical A/D converter, such as TMP 112\(^{34}\) which requires
energy of 25.2 µJ for one-time operation. Similarly, for typical CO/heat detector, such as
E46C800\(^{35}\), 36 minutes is sufficient for one-time operation. In addition, AD5933\(^{36}\) employed
particularly for electro-mechanical impedance (EMI) based SHM, could be powered for one-time
from 6.16 hours of harvested energy from the real-life bridge vibrations. Thus, Table 6 has shown
practical applications of PEH from a typical city flyover.

Table 7 shows the comparison of laboratory and field experiments for harvested power
accumulated in battery using MFC under the nearly same condition of frequency (4 or 5 Hz). It
can be seen from the table that harvested power achieved in the laboratory and field are 0.15 mW
in 1.20 hours and 0.17 mW in 8.08 hours, respectively. The significant reason for long charging time in case of field experiment despite higher voltage amplitude is due to the discontinuous and intermittent vibrations of the host structure. The power density (based on area) of the MFC patch (with an active area 23.8 cm$^2$) for laboratory and field experiments are 6.30 µW/cm$^2$ and 7.14 µW/cm$^2$ respectively. The Power density is higher in case of field experiment as compared to laboratory experiment due to the reason of higher impact factor of moving load.

5. CONCLUSIONS

This paper presents laboratory and field investigations of D1000 rectifier circuit for charging a rechargeable battery from the energy harvested from real-life bridge using the directly bonded piezoelectric elements. The output from the piezoelectric element was fed directly to the D1000 rectifier circuit. A rechargeable battery of 15 mA\(h\) capacity was connected to the output of the circuit. The battery was allowed to charge to its full potential. Initial experiments were conducted in laboratory simulating real-life conditions of low-frequency and low-voltage amplitude expected from civil-structural vibrations. Harvested power of 1 mW and 7 mW for \(V_{oc} = 4\) V and 0.15 mW and 0.18 mW for \(V_{oc} = 1\) V was achieved at 5 Hz and 10 Hz respectively from the MFC patch by employing optimized D1000 rectifier circuit is feasible. The next experiment was performed for charging a rechargeable battery from the energy harvested from wind induced vibrations using the piezoelectric elements. Harvested power of 0.36 µW and 7.9 µW was achieved for maximum and minimum fan speed, respectively. Lastly, field investigations for charging the rechargeable battery from the energy harvested from a real-life bridge vibration was carried out. A harvested power of 0.27 mW was achieved from the PCH. The MFC and the PZT patches bonded directly in \(d_{31}\) configuration on the girder were next investigated for energy harvesting potential. The harvested
power was measured as $0.17 \text{ mW}$ and $1.56 \mu \text{W}$ respectively for the MFC patch and PZT patches.

In addition to the battery, a capacitor was also evaluated, and it could produce a power of $0.5 \text{ nW}$ from the directly bonded PZT patch in the $d_{31}$ configuration. Experimental results show that it is feasible to charge a battery under low-frequency ($<5 \text{ Hz}$) and a small voltage scenario ($V_{oc} = 1 \text{ V}$) by employing an optimized D1000 rectifier circuit. Thus, the charging of the battery was successfully demonstrated in a simple $d_{31}$ configuration from a real-life structure. To the best of this author’s knowledge, this is the first proof-of-concept real-life demonstration of this kind.

In a nutshell, feasibility of PEH and energy storage using piezoelectric elements bonded directly to the host structure operating in the $d_{31}$-mode has been explored experimentally and successfully demonstrated in a realistic environment, that of a real-life bridge under operational conditions. This marks establishment of TRL of 7.0, which is the main contribution of this paper.

DATA AVAILABILITY STATEMENT

All data, models, and code generated or used during the study appear in the submitted article.
REFERENCES


5. Balguvhar S. “Piezoelectric energy harvesting through low frequency non sinusoidal vibrations of civil structures” Ph.D. Thesis, 2020, Department of Civil Engineering Indian Institute of Technology, Delhi


Figure 1: A typical piezoelectric plate patch with 1, 2 and 3 axes

Figure 2: Bridge rectifier circuit
Figure 3: Experimental set-up for open circuit voltage from MFC patch bonded on cantilever beam
Figure 4. Typical open circuit voltage pattern (a) $V_{oc} = 1$ V and (b) $V_{oc} = 4$ V from MFC patch bonded on cantilever beam
Figure 5: Time domain plot of acceleration at mid-point of side girder.
Figure 6: Charging of battery from MFC patch for $V_{oc}= 4$ V and 1 V at frequency of 5 Hz and 10 Hz

Figure 7: Discharging curve of battery across 4.7 kΩ load resistor for $V_{oc}= 4$ V and 1 V at frequency of 5 Hz and 10 Hz
Figure 8: (a) Energy accumulated (b) Harvested power from MFC patch at 5 Hz and 10 Hz for $V_{oc} = 1$ V and 4 V
Figure 9: Experimental set-up for PEH from wind vibrations
Figure 10: (a) Structure of harvester
(b) Top view of the energy harvesting structure for wind induced vibration
Figure 11: Typical open circuit voltage from PZT patch bonded on cantilever beam at (a) minimum wind speed of 1.6 m/s and (b) maximum wind speed of 3.2 m/s
Figure 12: Frequency domain plot from PZT patch bonded on cantilever beam (a) minimum wind speed of 1.6 m/s and (b) maximum wind speed of 3.2 m/s
Figure 13: Charging curve of battery at (a) maximum wind speed of 3.2 m/s (b) minimum wind speed of 1.6 m/s
Figure 14: Discharging curve of battery across 4.7 kΩ load resistor for (a) maximum wind speed of 3.2 m/s (b) minimum wind speed of 1.6 m/s
Figure 15: General view of Jia Sarai Flyover from IIT Gate
Figure 16: (a) PCH with MFC (b) Frequency domain plot of PCH
Figure 17. PCH with MFC piezo patch attached underneath steel girder

Figure 18: Plot of open circuit voltage from MFC patch installed on PCH as function of time
Figure 19: Installation steps for PZT patch
(a) PZT patch freshly pasted on epoxy layer
(b) PZT patch covered with a magnet for curing (c) Connection wires soldered on PZT patch after 24 hours of curing (d) PZT patch covered with epoxy for protection

Figure 20: Close up of broken PZT patch bonded on girder
Figure 21: Installation steps for MFC patch
(a) MFC patch freshly pasted on epoxy layer (b) MFC patch covered with a magnet for curing (c) Connection wires soldered on MFC patch after 24 hours of curing (d) MFC patch covered with epoxy for protection
Figure 22: Typical open circuit voltage from
(a) PZT patch (b) MFC patch
Figure 23: Frequency domain plot of voltage from (a) PZT patch (b) MFC patch bonded on girder
Figure 24: Experimental setup for field power measurement
Figure 25 (a) Charging curve (b) discharging curve of battery across 4.7 kΩ load resistor for PCH
Figure 26: Charging of battery from piezo patches bonded directly on girder
(a) MFC patch (b) PZT patch
Figure 27: Discharging curve of battery across 4.7 kΩ load resistor for piezo patches bonded directly on girder (a) MFC patch (b) PZT patch
Figure 28: Charging of capacitor from PZT patch bonded directly on girder
### Table 1: Technology Readiness level

<table>
<thead>
<tr>
<th>TRL</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Physical principles are postulated with reasoning</td>
</tr>
<tr>
<td>2</td>
<td>Applications for physical principles identified but no results</td>
</tr>
<tr>
<td>3</td>
<td>Initial laboratory tests on general hardware configurations to support physical principles</td>
</tr>
<tr>
<td>4</td>
<td>Integration level showing systems function in labs test</td>
</tr>
<tr>
<td>5</td>
<td>System testing to evaluate function in realistic environment</td>
</tr>
<tr>
<td>6</td>
<td>Evaluation of prototype system</td>
</tr>
<tr>
<td>7</td>
<td>Demonstration of complete system in operating environment</td>
</tr>
<tr>
<td>8</td>
<td>Certification testing on final system in lab and/or field</td>
</tr>
<tr>
<td>9</td>
<td>Final adjustment of system through mission operations</td>
</tr>
</tbody>
</table>

### Table 2: Efficiency comparison of Circuits

<table>
<thead>
<tr>
<th>Circuit Type</th>
<th>1 V 5 Hz</th>
<th>1 V 15 Hz</th>
<th>4 V 5 Hz</th>
<th>4 V 15 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1000</td>
<td>81.33%</td>
<td>72.55%</td>
<td>69.10%</td>
<td>62.55%</td>
</tr>
<tr>
<td>D5819</td>
<td>32%</td>
<td>39.09%</td>
<td>31.64%</td>
<td>44.04%</td>
</tr>
<tr>
<td>DMOS</td>
<td>9.3%</td>
<td>14.28%</td>
<td>9.37%</td>
<td>16.36%</td>
</tr>
<tr>
<td>GFCMOS</td>
<td>13.33%</td>
<td>25.18%</td>
<td>47.28%</td>
<td>52.24%</td>
</tr>
<tr>
<td>GCMOS</td>
<td>11.33%</td>
<td>20.30%</td>
<td>16.50%</td>
<td>23.22%</td>
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### Table 3: Properties of PZT and MFC patch\(^{31,33}\)

<table>
<thead>
<tr>
<th>Property</th>
<th>Parameter</th>
<th>PZT</th>
<th>MFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan size (mm(^2))</td>
<td></td>
<td>10 × 10</td>
<td>85 × 28</td>
</tr>
<tr>
<td>Thickness, (h) (mm)</td>
<td></td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Piezoelectric Strain Coefficient, (d_{31}) (m/V)</td>
<td></td>
<td>-2.10 × 10(^{-10})</td>
<td>-1.71 × 10(^{-10})</td>
</tr>
<tr>
<td>Young’s Modulus, (Y_E) (N/m(^2))</td>
<td></td>
<td>6.667 × 10(^{10})</td>
<td>6.667 × 10(^{10})</td>
</tr>
<tr>
<td>Electric Permittivity, (e_{33}) (F/m)</td>
<td></td>
<td>2.124 × 10(^{-8})</td>
<td>8.85 × 10(^{-12})</td>
</tr>
</tbody>
</table>

### Table 4: Properties of Glass-fibre composite Cantilever Beam

<table>
<thead>
<tr>
<th>Property</th>
<th>Parameter</th>
<th>Glass-fiber composite cantilever beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical Properties</td>
<td>Cross Section (mm(^2))</td>
<td>35 × 1</td>
</tr>
<tr>
<td></td>
<td>1(^{st}) natural frequency (Hz) (Theoretical)</td>
<td>4.39</td>
</tr>
<tr>
<td>Material Properties</td>
<td>Young’s Modulus, (Y_E) (N/m(^2))</td>
<td>12 × 10(^9)</td>
</tr>
<tr>
<td></td>
<td>Density (Kg/m(^3))</td>
<td>5440</td>
</tr>
</tbody>
</table>
### Table 5: Properties of Aluminium Cantilever Beam

<table>
<thead>
<tr>
<th>Properties</th>
<th>Parameters</th>
<th>Aluminium cantilever beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical Properties</td>
<td>Length (mm)</td>
<td>200</td>
</tr>
<tr>
<td>Cross Section (mm × mm)</td>
<td></td>
<td>35×0.5</td>
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<tr>
<td>Material Properties</td>
<td>Young’s Modulus, ( Y_e ) (N/ m²)</td>
<td>6.9×10^{10}</td>
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<tr>
<td></td>
<td>Density (Kg/m³)</td>
<td>2715</td>
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### Table 6: Charging cycles time for different circuits for various applications

<table>
<thead>
<tr>
<th>Circuit/IC</th>
<th>Energy required</th>
<th>4 Hz at 0.78 V (26 mJ)</th>
<th>Charging cycles</th>
<th>Charging Time</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical A/D Convertor, TMP 112(^{34})</td>
<td>25.2 µJ</td>
<td>12 minutes</td>
<td>0</td>
<td>12 minutes</td>
<td>Industrial Application</td>
</tr>
<tr>
<td>E46C800(^{35})</td>
<td>3 mJ</td>
<td>36 minutes</td>
<td>0</td>
<td>36 minutes</td>
<td>CO/heat detector</td>
</tr>
<tr>
<td>AD5933(^{36})</td>
<td>33 mJ</td>
<td>6.168 hours</td>
<td>1.26</td>
<td>6.168 hours</td>
<td>SHM</td>
</tr>
</tbody>
</table>
Table 7: Comparison of harvested power in battery using MFC

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Laboratory Experiment</th>
<th>Field Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvested Power (mW)</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Charging time (hours)</td>
<td>1.20</td>
<td>8.08</td>
</tr>
<tr>
<td>Input Voltage (V)</td>
<td>1</td>
<td>2.5</td>
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</table>