ABSTRACT

Driven by technological advancements and accelerated infrastructure development, an increase in the need to monitor the performance of prominent structures such as buildings, tunnels, bridges, metro corridors, and sea-link bridges is being advocated by experts to predict and minimize any hazards resulting from structural degradation over time. However, when the sensors are instrumented in remote locations, it becomes very expensive to access them and replace their batteries. Thus, harvesting and storing ambient energy from the surroundings to drive the sensors for structural health monitoring (SHM) holds a great importance to be explored. There are several sources to harvest energy namely, wind, solar and ambient vibrations. Piezoelectric energy harvesting uses ambient vibrations to harvest energy. In the case of civil engineering structures such as buildings, tunnels and bridges, the primary challenge is to capture the voltage generated from the ambient vibrations, as they are of very low amplitude and frequency. Various kinds of embedded piezoelectric harvesters are reported in the literature including curved piezoelectric energy harvesters. However, there are certain practical issues and limitations associated with the embedded piezoelectric harvesters as they are suitable only for flexible transducers and concrete constructions.

The main motivation of this doctoral research is to attain a cost-effective solution for strain amplification that enhances the sensitivity of the conventional sensors by simple geometrical modifications. The main objective of this research is to explore the possible use of the non-rectilinear configuration of the piezoelectric energy harvesting, by addressing all the limitations posed by the embedded type curved energy harvesters.

The research aims to introduce a novel trapezoidal strain amplifying sensor/energy harvester (TSAH) for civil engineering structures leveraging flexural strain amplification to enhance

energy harvesting from structural vibrations. The proposed TSAH sensors cum harvesters are suitable for both flexible and brittle-type transducers. Since they are primarily externally attached, TSAH can be replaced in case of any faulty performance of the transducer. Additionally, it allows for replacement and reuse, which furthers the goal of sustainability. This makes it possible to harvest green energy, which can be used to power the batteries in wireless sensors. The proposed TSAH has the practical prospects of the innovation for enhanced energy harvesting and structural health monitoring in civil constructions simultaneously.

The research first examines the influence of the geometric properties of TSAH on strain amplification via numerical investigations under a specific set of external loads. Further, analytical equations are derived considering the TSAH structure as an inclined portal frame. It was observed that its strain amplification follows the same trend as that obtained in the numerical analysis with somewhat lesser amplification. This may be due to the assumptions considered in the analytical modelling of the TSAH itself.

Further, experimental investigations are carried out first in the laboratory to evaluate the effectiveness of the TSAH over the directly bonded (DB) sensor cum harvester on a prototype model of the foot-over bridge. It is found that the TSAH outperformed the DB sensor cum harvesters. The typical amplification factors of TSAH for peak voltage is found to be between 1.45 and 3.75, while for power, it lies between 1.09 and 6.08 for the various scenarios taken into consideration in the lab study. Further, for field verification, the TSAH configuration is evaluated on a real-life bridge structure, viz the Chipiyana road over-bridge (ROB) located on the Delhi-Meerut expressway. The field experiments also establish the superior performance of TSAH, with an amplification factor ranging from 1.75 to 3.75 for peak voltage and 3.75 to 5.53 for peak power.

This research also explores the possibility of using the TSAH for SHM as well as energy harvesting on real-life civil structures such as bridges. As such, the power storing potential of the TSAH and the DB harvesters in storage elements such as capacitors and batteries is experimentally evaluated. Initially, this research examines the laboratory viability of storing the piezoelectric energy captured via shaker vibrations in capacitors and batteries. During the lab investigations, it is noticed that the power storing ability of the TSAH is 2.7 times that of the DB harvester in the case of capacitor. However, it is found that the capacitor discharges almost immediately. Therefore, charging trials are repeated on nickel metal hydride (Ni-MH) rechargeable battery. The laboratory trials revealed that the TSAH could store 2.6 times more energy in the battery when compared to the DB harvester. According to the extended statistical laboratory results on battery charging, the TSAH requires only half the time of the DB harvester to charge a 3.6 V rechargeable battery. The field studies on the ROB are carried out to capture and store the energy from the traffic-induced vibrations in the capacitor. It is discovered that, after charging the capacitor continuously for an hour, the power stored by TSAH is 8 times that of the DB harvester. Laboratory and field investigations establish that the TSAH has greater power storage capability as compared to the DB harvester.

In addition to its improved harvesting capabilities, the TSAH also functions as a strain sensor. When compared to the DB sensors, the TSAH offers a higher sensing ability because of its strain amplification potential. Hence, the TSAH is evaluated as a sensor-cum-harvester for integrated SHM and energy harvesting. The damage detection potential of the TSAH is evaluated in the laboratory using the EMI technique and the curvature modal analysis. The root mean squared deviation (RMSD) values demonstrate that the TSAH offers a higher damage detection capacity when compared to the DB sensor. Furthermore, the TSAH determined the exact damage location with greater accuracy, achieving 93.26% compared to 85.50% for the DB sensor-cum-harvester. An optimized impedance model is developed by validating it against the experimentally obtained conductance and susceptance signatures. This model is then used to determine the equivalent structure parameters (ESP) namely, mass (*m*), stiffness (*k*), and the residual stiffness of the structure after damage. Compared to DB sensors, the TSAH recorded a greater change in stiffness caused due to damage indicating the higher sensitivity of the TSAH when compared to the DB sensor.

As compared to the previously proposed curved configuration in the literature, the TSAH configuration is suitable for brittle sensors as well. Its ability to be permanently bonded by epoxy/ welding or temporarily, using magnets, bolts, or clamps, offers greater versatility over other surface bonded/ embedded configurations. This imparts reusability in case of any damage, ensuring achievement of the goal of sustainability. It is expected that the outcomes of the research shall contribute significantly in the field of piezoelectric energy harvesting from the real-life structures.