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Self-powered piezo-floating-gate sensors for health monitoring of steel plates

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ABSTRACT

This paper presents a new method for structural health monitoring using self-powered piezo-floating-gate (PFG) sensors with variable injection rates. An experimental study was performed on an A36 thin steel plate subjected to an in-plane tension mode to verify the proposed method. Different piezoelectric transducers were mounted on the plate for both empowering the sensor and monitoring the damage progression. The changes of charge on the floating-gates of the sensor due to electron injection were considered as damage indicator parameters. In order to improve the damage detection accuracy, several features were extracted from the cumulative voltage droppage for each memory gate, based on sensor group concept. The obtained features were then fed into a support vector machine (SVM) classifier to identify multiple damage states. An optimization process was developed to optimize the parameters of the classifier in order to increase the detection rate accuracy. Based on the results, the performance of the proposed method is satisfactory for detecting damage progression in steel plates.

1. Introduction

Wireless sensor networks (WSNs) are widely used as alternatives to traditional structural engineering monitoring systems. The significant capability of WSNs for sensing the physical state of the structural systems has attracted considerable attention in recent years [1–10]. Recent development and applications of smart sensors and sensing systems in structural/infrastructural engineering can be found in [11–14]. However, a significant concern for the application of wireless sensors is their power supply. Nearly all of the commercially available sensors for structural health monitoring (SHM) require an external power source, either battery or solar power [15]. Periodic replacement of batteries for embedded sensors, or use of solar power technology, would be cost-prohibitive and in some cases impractical. This issue becomes more challenging for the continuous long-term monitoring of steel structures. Harvesting ambient energy seems to be an attractive solution for tackling this problem [2,11,16–20]. Energy harvesting devices can convert mechanical energy into electrical energy [21]. These micro-power generators can be used and integrated with the monitoring system. Among various self-powering energy sources, piezoelectric transducers have been shown to be one of the most efficient choices [22–26]. For SHM, piezoelectric transducers can be used for the self-powering of wireless sensors by harvesting energy from the mechanical loading experienced by the structure [27–30].

Recently, the authors have developed a new class of self-powered wireless sensor (SWS) [26–30]. This sensor uses piezoelectric transducers to empower an array of ultra-low power floating-gate computational circuits. The SWS has a series of memory cells that cumulatively store the duration of voltage when the amplitude of the input signal, coming from the piezoelectric material, exceeds different thresholds. The recorded cumulative durations are stored on-board the sensor from the time it is installed, and can be periodically read using a Radio Frequency Identification (RFID) scanner [26–28]. One of the main advantages of this sensing system is the fact that it is "response-based". All the effects due to variations in load location, load magnitude, traffic wander, environmental effects such as temperature and moisture, and material aging and degradation, are aggregated in the strain response recorded by the sensor over time. This feature makes the sensor suitable for long-term SHM. Most of the other existing solutions

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evaluate the condition of the system at a given instant. These methods present only a snapshot at the time where the measurements are taken. Thus, the obtained results are highly influenced by the environmental conditions. Since the developed SWS records each and every event all the time, it will aggregate all these short-term fluctuations. Thus, if long-term shifts are observed in the results, they are most probably correlated with condition degradation. Herein, the whole methodology is based on relative damage as the sensor does not directly measure the absolute value of strain. The rate of variation of strain distributions is related to the rate of damage. Fig. 2 shows the SWS and a schematic representation of its working mechanism. This piezo-floating-gate (PFG) sensor is fabricated using a p-channel floating-gate metal-oxidesemiconductor (pMOS) transistor [23,25]. The transistor is connected to a constant current source powered by the piezoelectric transducer. The piezoelectric transducer harvests the energy that will be used to inject electrons from the transistor channel into the floating-gate. The impact-ionized hot-electron injection (IHEI) model can be used to derive the change/droppage of the floating-gate voltage with respect to time and drain current. Subsequently, for long-term monitoring, the cumulative duration for which the injector is operational can be obtained using the measured floating-gate voltage [23,25]. However, the prototypes of the sensor can have floating-gates with constant and variable electron injection rates. The floating-gate injection rate (I_{inj}) is a property of the gate that controls the injection of the electrons into the gate. This parameter is correlated with the voltage droppage rate (V_{inj}) across the gate. The rate V_{inj} is defined as the voltage droppage during one second of injection of electrons. Fig. 1(c) and (d) show an illustrative example of the voltage droppage calculation for gates with constant and variable injection rates, respectively. Note that the cumulative time at specific strain/voltage threshold level is proportional to the voltage droppage across the memory gate. As seen in Fig. 1(c) and (d), gates 1 to 3 can record the changes of voltage on the floating gates due to electron injection for a random excitation given in Fig. 1(a). On the basis of previous research [27–30], the output of the sensor with the constant injection rates can be characterized by a Gaussian cumulative density function (CDF). In this case, the mean of the cumulative time distribution (μ) and the standard deviation (σ) accounting for the load and frequency variability can be considered as viable tools to define the SWS output data. These parameters can be obtained by curve fitting of the sensor output distribution collected from the entire memory cells, as indicated in Fig. 1(c). Research in the previous FHWA funded project [27–30] showed that damage progression in structures could be monitored by tracking the changes of μ and σ over time, and utilizing robust soft-computing techniques. As can be observed from Fig. 1(d), analysis of the sensor outputs becomes more challenging for the case of a sensor with variable injection rates. This is because the cumulative voltage droppage histogram could not be fitted to a Gaussian distribution.

The main goal of this study is to evaluate the performance of the self-powered PFG sensors for the detection of damage progression in steel plates under a uniaxial tension mode. This type of testing is widely used in SHM to assess the integrity of plate-like structures for aerospace, civil and mechanical applications [31]. The objective of this work is to validate the proposed sensing technology through small-scale laboratory testing as the stepping-stone for the next phase of the project on full-scale structures. To this aim, an in-plane tension test was carried out the on a thin steel plate with different notch sizes. Several piezoelectric transducers were installed on the plate to measure the changes of charge in the floating-gates due to damage progression. The cumulative voltage droppage for each memory gate was used to extract damage indicator features. A support vector machine (SVM) classification approach was then utilized for multiclass damage detection. The obtained trends were analyzed and discussed in this paper in detail.

2. Self-powered PFG sensor

2.1. Working mechanism of the SWS with non-constant injection rates

It is known that piezoelectric materials have the ability to convert mechanical applied loading to an electrical charge, using the direct piezoelectricity effect. The open source voltage (V) generated across the piezoelectric lead zirconate titanate (PZT) ceramic

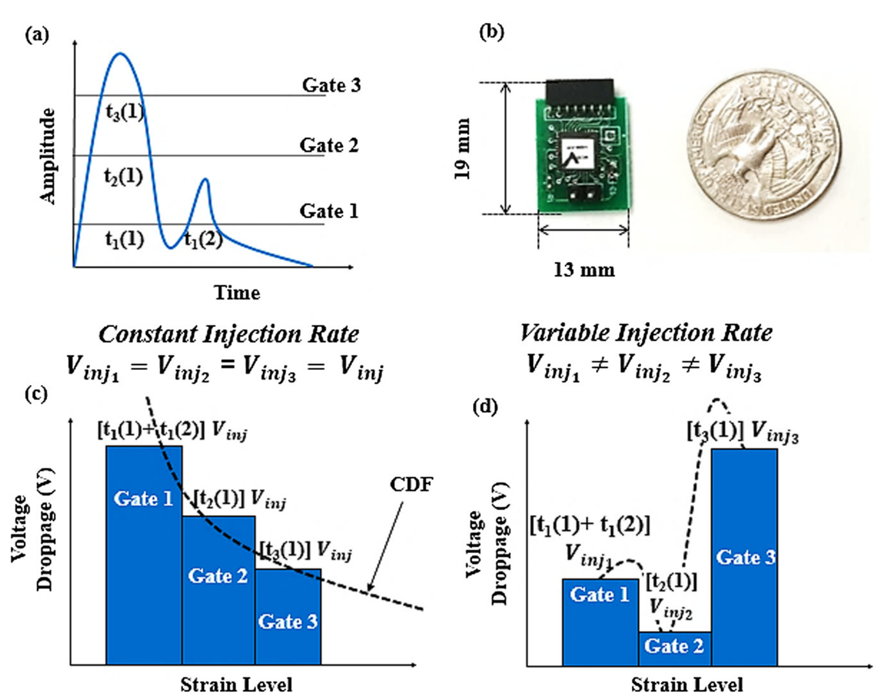

Fig. 1. Prototype and working principle of the self-powered PFG sensor.