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Continuous health monitoring of pavement systems using smart sensing technology

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HIGHLIGHTS

- A self-powered sensing approach is proposed for health monitoring of pavement systems.
- Damage detection performance is evaluated with numerical and experimental studies.
- A new miniaturized spherical packaging system is designed for the protection of embedded sensing system.
- Damage localization and quantification is investigated.

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ABSTRACT

Recently, significant attention has been devoted to the utilization of new sensing technologies for pavement maintenance and preservation systems. This study presents a new approach for the continuous health monitoring of asphalt concrete pavements based on piezoelectric self-powered sensing technology. The beauty of this technology is that the signal sensed by the piezoelectric transducers from traffic loading can be used both for empowering the self-powered sensors and damage diagnosis. Numerical and experimental studies were carried out to evaluate the damage detection performance of the proposed self-sustained sensing system. A three-dimensional finite element analysis was performed to obtain the pavement responses under moving tire loading. Damage was introduced as bottom-up fatigue cracks at the bottom of the asphalt layer. Thereafter, features extracted from the dynamic strain data for a number of sensing nodes were used to detect the damage progression. The laboratory tests were carried out on an asphalt concrete specimen in three point bending mode. For the protection of the embedded sensors, a new miniaturized spherical packaging system was designed and tested. Based on the results of the numerical study, the sensing nodes located along the loading path are capable of detecting the damage progression. Besides, the experimental study indicates that the proposed method is efficient in detecting different damage states including crack propagation. Finally, the possibility of localizing the damage and quantifying its severity was investigated and discussed.

1. Introduction

Pavement health monitoring plays a key role in pavement management systems. Early repair and maintenance scheduling increase the safe operation and in-service performance of pavement. This can be achieved through an accurate and consistent monitoring of pavement condition. In general, the existing approaches for pavement health monitoring can be divided into external evaluation technologies and in situ pavement sensors [1]. The external evaluation methods have been commonly used for the evaluation of surface distresses. Typical examples in this context are using image analysis techniques to analyze the pavement distress [2,3], or stereo-imagery for measuring pavement deformation [4]. Besides, there are numerous nondestructive evaluation (NDE) methods for the assessment of assess the behavior of pavements and other infrastructures [5–18]. The in-situ pavement sensing methods have been the focus of many studies for the last decades as alternatives to the traditional monitoring [19–22]. Different type of sensors can be used in this domain such as pressure cell, deflectometer, strain gauge, thermocouple, moisture sensor, fiber-optic sensors, etc [23–34]. Moreover, there are several full-scale test studies to measure the in situ pavement responses under traffic load [35–37].

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A major limitation of the traditional wired sensors pertains to their deployment and maintenance. More, managing huge amount of data generated by a dense array of wired sensors is very challenging and costly [38]. To cope with these limitations, wireless sensor networks (WSNs) are increasingly utilized 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 [39–46]. WSNs are not merely monitoring systems but also autonomous data acquisition nodes [47–49]. Dense arrays of low-cost smart wireless sensors can offer useful data about the structural deterioration. Such information can be efficiently used to enhance the performance of the pavement condition monitoring systems [38,50,51]. Recent development and applications of smart sensors and sensing systems in infrastructural engineering can be found in [38,52–56]. However, a significant concern for the application of wireless sensors is about their power supply. Nearly all of the commercially viable sensors for structural health monitoring (SHM) require an external power source, either battery or solar power [57]. 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 pavement structures. Harvesting ambient energy seems to be an attractive solution for tackling this problem [54,58–61]. Energy harvesting devices can convert mechanical energy into electrical energy [62]. These micro-power generators can be used and integrated with the monitoring system. Among various self-powering energy sources, piezoelectric transducers are proved to be one of the most efficient choices [57–64]. For pavement health monitoring, piezoelectric transducers can be used for the self-powering of wireless sensors by harvesting energy from the mechanical loading experienced by the pavement [64]. Recently, the authors at Michigan State University (MSU) have developed a new class of self-powered wireless sensors (SWS) [63–65]. The designed SWS is a small size battery-less sensor. The prototype of this miniaturized strain-senor is shown in Fig. 1.

This unique sensor is based on the integration of the piezoelectric transducers with an array of ultra-low power floating gate computational circuits [64]. By embedding these sensors inside the pavement, it is possible to monitor the localized strain statistics. The recorded information can be used for early damage detection and future condition evaluation. Research in the previous FHWA funded project revealed the applicability of the SWS for continuous monitoring of infrastructures [63–66]. That project was basically focused on the manufacturing of the sensor electronics, and design of a packaging system to withstand loading and environmental conditions for the pavement implementation. A limited study was done on developing a method for predicting remaining fatigue life of pavement and generating missing data from a set of measurements by a classical statistical technique [64]. Despite several advantages of using SWS, there would be a considerable loss of information. In fact, a part of the sensed information is

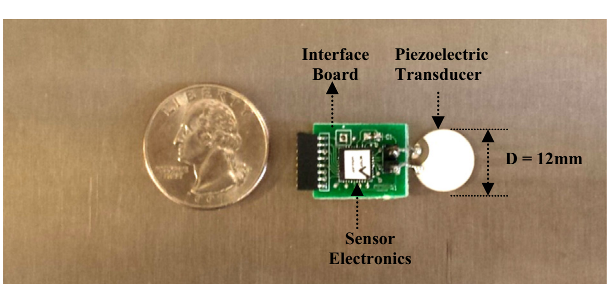

Fig. 1. The prototype of the SWS system.

compressed as a function of cumulative time at each load level. This drawback results in a difficulty in the interpretation of the data generated by SWS [64]. More recently, Alavi et al. [65] proposed a data interpretation system integrating finite element method (FEM) and probabilistic neural network (PNN) for the detection damage progression in gusset plates based on the SWS data.

This study presents a new system for the continuous long-term health monitoring of pavement structures based on the SWS data. The proposed approach uses features extracted from the cumulative time strain distributions at preselected discrete levels. The finite element model of an asphalt concrete pavement layer was used as the representative of the real structure. The main goal was to detect the fatigue cracking due to excessive tensile strain at the bottom of the asphalt concrete. In order to analyze the response of the sensing system embedded within the asphalt layer, a series of tests were conducted on an asphalt concrete beam under a three point bending configuration. The results indicate that the proposed system can be efficiently used for the pavement health monitoring.

2. The proposed pavement health monitoring system

Damage detection algorithms play a key role in the SHM systems. These algorithms are used for the analysis of raw sensor data and subsequently for damage diagnosis [67]. The SWS-based damage detection procedure proposed in this study includes three major phases: (1) structural simulation with finite element method (FEM) (2) generation of data and feature extraction based on the outputs of the SWS memory cells, and (3) finding a reasonable relationship between the probability density function (PDF) parameters obtained from strain distribution, and damage progression. First, a damage scenario was defined for the given pavement structure via the FE simulations. Subsequently, the cumulative time of occurrences at predetermined strain levels are determined for the data acquisition points (sensors). The strain distribution in each sensing node was used for defining damage indicators. Besides, a major challenge in application of wireless sensors results from the fact that damage in structures is an intrinsically local phenomenon. Thus, sensors that are close to the damaged site are more influenced than those remote to the damage site. The only existing solution to effectively detect damage at an arbitrary location in a structure is to densely distribute the sensors throughout the structure [38]. Obviously, this is not an optimal and economic solution. To cope with this issue, this study proposes another strategy based on the effect of array of sensors.

2.1. Smart sensor

The new smart SWS made at MSU is capable of continuously monitoring of strain events within the host structure. It uses only self-generated electrical energy harvested directly from the sensing signal induced by a piezoelectric transducer connected to the pavement. This sensor can be economically attached to pavement structures either during construction, or anytime during routine maintenance operations. The communication between the sensor and a service vehicle is done using Radio Frequency Identification (RFID) technology. Previous study showed that the sensor can be read using an RFID scanner from a distance of 16 in. (406.4 mm) [64]. For a sensing system embedded inside an asphalt specimen, the thickness of the asphalt layer affects the accuracy of the transmitted and recovered signal due to its viscoelastic properties. In this case, the sensor and RFID scanner can communicate from a distance of about 12 in. (304.8 mm) [64]. The convertible electrical power levels in structures are typically less than 1 μW. Given the strain levels observed in pavements, it is believed that the available