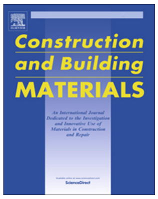
Construction and Building Materials 76 (2015) 187–193

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat



Temperature and loading effects of embedded smart piezoelectric sensor for health monitoring of concrete structures

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HIGHLIGHTS

- Novel embedded piezoelectric sensor for SHM of concrete structure was developed.
- Influence of temperature on EMI method were studied at different frequency ranges.
- The electromechanical impedance responds differently to load from orthotropic direction.

ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form 26 November 2014
Accepted 29 November 2014
Available online 13 December 2014

Keywords:
Piezoelectric
Impedance
Concrete
Structural health monitoring

ABSTRACT

A kind of embedded impedance-based piezoelectric sensor was fabricated by using mixture of cement powder and epoxy resin as packaging layer. Effects of temperature and load on impedance and conductance spectra of the sensor were investigated. The results show that the baseline of conductance spectra shifts with increasing temperature, and the resonance peaks in the conductance spectra show obvious temperature dependence. The impedance spectra of the embedded sensor under external load from different direction was discussed. The results indicate that the sensor is sensitive to the initial load when the external load is parallel to the thickness direction of the sensor. When the load is along the planar direction of the sensor, the impedance spectra of the sensor show good correlation with the load variation. The root mean square deviation (RMSD) index was also employed here to intuitively indicate the impedance variation of the embedded PZT sensor under temperature and load.

1. Introduction

In the last few decades, structural health monitoring (SHM) is becoming increasingly popular due to the development of smart materials system and structure, in which piezoelectric materials are particularly concerned because of its positive and reverse piezoelectric effects. Presently, many SHM techniques with regard to piezoelectric materials have been developed to assess the safety and integrity of in-situ structures, such as acoustic emission technique [1], wave propagation technique [2], and stress/strain technique [3]. Electromechanical impedance (EMI) technique is considered to be one of the most promising approaches of these piezoelectric SHM techniques due to its high sensitivity to local incipient damage and low-cost.

The mechanical impedance of structure changes when being damaged, thus EMI technique is developed to monitor a local area of the host structure by utilizing the electro-mechanical coupling capability of piezoelectric materials. The application of impedance measurements to structure health monitoring has its theoretical development first proposed by Liang et al. [4], and subsequently developed by Sun et al. [5], Park et al. [6–9], Giurgiutiu et al. [10–12], Soh et al. [13,14], Yang et al. [15–17]. In 1999–2001, Park et al. [6–8] detected the bolted joint structure, civil structure component and built-in pipeline by using EMI technique. In 2000, Soh et al. [13] monitored the RC bridge by using the EMI method and provided a procedure to interpret a signal from debonding or breakdown of the PZT sensors. In 2002–2004, Tseng et al. [18,19] presented numerical studies by using surface-bonded impedance sensors to monitor two types of damage (i.e. void ad crack) in a concrete structure. In 2008, Yang et al. [15,16] studied the problems involved in real-life applications of the EMI technique and concluded the relationship between PZT bonding thickness and temperature. In addition, they also proposed a reusable PZT

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http://dx.doi.org/10.1016/j.conbuildmat.2014.11.067

transducer in recent years for monitoring initial hydration and structural health of concrete [17]. Although EMI technique shows the characteristics of high sensitivity to incipient damage of host structure, practical problems have hindered the efficient and reliable application of EMI to real-world structures. Various factors such as environmental conditions, variation of static or dynamic loads will inevitably influence the monitoring accuracy of the EMI technique as well as the service life of the piezoelectric sensors. Therefore, it is important to develop a kind of embedded piezoelectric sensor suitable for concrete structure to improve not only the service-life of the sensor, but also the monitoring accuracy of the EMI technique.

Here a kind of embedded piezoelectric sensor for concrete SHM application was developed by using PZT piezoelectric ceramic as sensing element and mixture of cement powder and polymer as packaging layer. Because the cement/polymer packaging layer has the characteristics of high strength and good insulation ability, the service-life and long-term stability of the proposed sensor can be improved when embedded into concrete structure. It is known that temperature and stress are two important environmental loads in practical engineering fields, and the correlated EMI research referring to temperature and stress load have also been reported [20–23]. Therefore, the effects of temperature and compressive load on impedance spectra of the proposed embedded sensor were investigated in this work, and meanwhile a root mean square deviation (RMSD) method based on EMI spectra of the sensors was also developed.

2. Experimental procedure

2.1. EMI method principle

The piezoelectric materials will vibrate under the alternating electric field, and accordingly cause the vibration of structure when coupled to structure. It is known that the mechanical impedance of structure changes with occurrence of damage, thus the mechanical impedance information of structure can be obtained by analyzing the electric impedance variation of piezoelectric materials. Fig. 1 shows the one dimensional interaction model between the embedded piezoelectric sensor and structure, in which the packaging layer and the structure can be regarded as spring (k_1)–mass (m_1)–damp (c_1) and spring (k_2)–mass (m_2)–damp (c_2), respectively.

Based on the theoretical model proposed by Liang et al. [4], it is known that the electrical admittance $Y(\omega)$ of the PZT sensor is a combined function of the mechanical impedance $Z_a(\omega)$ of the PZT sensor and $Z(\omega)$ of the host structure.

$$Y(\omega)=\frac{I}{V}=i\omega a\left(\bar{\varepsilon}_{33}^{T}-\frac{Z(\omega)}{Z(\omega)+Z_a(\omega)}d_{3x}^{2}\bar{Y}_{xx}^{E}\right) \tag{1}$$

where V is the input voltage to the PZT sensor, and I is the output current from the PZT sensor. a, d_{3x}, $\bar{Y}_{xx}^{E}$, $\bar{\varepsilon}_{33}^{T}$ are the geometry constant, piezoelectric coupling constant, Young's modulus, and complex dielectric constant of the PZT sensor at zero stress, respectively.

Assuming that the mechanical property of the PZT sensor does not change over the monitoring period of the host structure, it can be clearly seen from Eq. (1) that the electrical impedance of the PZT sensor is directly related to the mechanical impedance of the host structure, consequently, any changes in the electrical impedance signature can be considered an indication of changes in the structural integrity [10]. Therefore, the mechanical properties of the host structure can be monitored by using the measured electrical impedance.

2.2. Preparation of the piezoelectric sensor

The PZT piezoelectric ceramic wafer with a thickness of 1.5 mm and a diameter of 20 mm was used as sensing element to fabricate the embedded piezoelectric sensor. Mixture of cement powder and polymer was used as waterproof packaging material of the sensor. The proportion of cement powder, epoxy resin and curing agent is 1:1:0.25 by weight. Fig. 2 shows the fabrication flow of the embedded PZT sensor.

The shielding wire was first soldered to the surface electrodes of the piezoelectric ceramic wafer, and then acetone was used to clean surface of the PZT ceramic. A mould was tailored by using the mixture of cement powder and polymer. The PZT ceramic was fixed in the mould, and the mixture of cement and polymer was then poured into the mould. After solidifying, the PZT sensor was successfully fabricated. It is known that the packaging layer can be regarded as the spring-mass-damping system, which will influence the vibration characteristic of the PZT element. Therefore, the thickness of packaging layer could not be too large in order to improve the impedance response of the sensor. Here the thickness of packing layer is about 5 mm.

2.3. Experimental setup

The impedance spectra of the embedded PZT sensor as a function of temperature and compressive load were investigated in this research, respectively. The temperature experiment was performed by embedding the PZT sensor into a mortar specimen with a dimension of 40 mm × 40 mm × 40 mm. The 42.5 ordinary Portland cement was used to fabricate the mortar specimen with water to cement ratio of 0.40. The mortar specimen with PZT sensor inside was put into the temperature test chamber (Model MPC-710) after curing for 28 d. The testing temperature range is −20 °C to 40°C with a heating rate of 2 °C/min, and the heat preservation time is 1 h every 10 °C. The impedance analyzer (Model Agilent 4294A) was used to test the electric impedance spectra of the sensor. According to the location of piezoelectric resonance peaks appeared in the impedance spectra, the frequency range of 0–100 kHz, 100–500 kHz and 600–1500 kHz were selected, respectively. The compressive load experiment was performed by using a compression-testing machine, and an increasing load with load step of 10 kN was applied to the mortar specimens until destruction. The applied load mode is shown in Fig. 3. Electric impedance spectra of the embedded PZT sensor were recorded every 10 kN. The frequency range of 20–180 kHz and 500–1500 kHz were selected here.

3. Results and discussion

3.1. Temperature effects

It is known that conductance is the reciprocal of resistance (i.e. real part of impedance). Because the impedance real part spectra of the sensor as a function of temperature is not very clear to observe

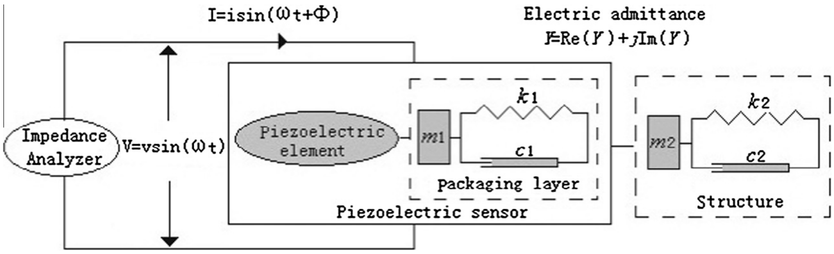

Fig. 1. One dimensional interaction model between piezoelectric sensor and structure.

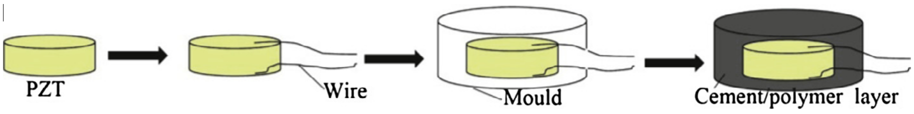

Fig. 2. Fabrication scheme of the embedded PZT sensor.