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Sensitivity of embedded active PZT sensor for concrete structural impact damage detection

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HIGHLIGHTS

- An innovative embedded 2D electromechanical impedance model was formulated.
- An experimental study on a concrete beam with impact damage was implemented.
- The embedded active PZT sensor was compared with surface-bonded ones in damage detection.
- The proposed embedded PZT sensor was validated that can filter out the external impact effect.

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ABSTRACT

Lead zirconate titanate (PZT) actuator/sensor is generally surface-bonded to structure in the electromechanical impedance (EMI) technique for structural health monitoring. However, in consideration of fragility and fugitiveness of surface-bonded PZT patch, it may lose serviceability when external impact happens especially in real-life applications. This paper covered the sensitivity of a new kind of embedded active PZT sensor in structural impact damage detection through theoretical and experimental analysis. Firstly, a new embedded 2D electromechanical impedance model was formulated, in which the PZT patch can be protected from external impact or disturbance. The proposed model was verified by experimental result of testing a manufactured embedded PZT sensor. Then the embedded PZT sensors were qualitatively compared with surface-bonded ones in the experiment of detecting a concrete beam which was damaged by successively knocking off concrete covers. Finally, the effectiveness of embedded PZT sensor in quantification on structural damage was investigated by using slope-based root mean square deviation (RMSD) index. Moreover, a new baseline-changeable RMSD index was also proposed to evaluate the impact effect for the two types of PZT sensor. It was found that the embedded PZT sensor can effectively filter out the impact effect in structural damage indication and quantification, which benefits the accurate evaluation on structural damage.

1. Introduction

Reinforced concrete is one of the most widely used construction materials in civil engineering structures including buildings, bridges, and dams, since it makes full use of superiorities of rebar and concrete, which possesses excellent tensile and compressive properties, respectively. As a necessary part, concrete cover protects the rebar from outside erosion, which can avoid decreasing the load-carrying capability of concrete structure. Unfortunately, external impact and denudation or internal shrinkage and creep often happen in real life which do harm to the collaboration of the two materials and even induce corrosion to rebar. This finally poses a threat to the security of concrete structures. Since most inaccessible locations of concrete engineering structures and components are difficult to be inspected, a non-destructive and real-time smart inspection method for impact damage detection of existing as well as to-be-built structures is a meaningful investigation which is always pursued by civil engineers.

Electromechanical impedance (EMI) technique as an effective non-destructive tool for structural health monitoring has gained significance in preventing premature failure of infrastructures, due to its merits of high sensitivity, fast response, easy installation, low cost and intelligent real-time detection [1–6]. Depending on the direct and converse effect of piezoelectric materials, the basis of EMI technique is to monitor the variations of admittance

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(inverse of impedance) caused by structural damages in the active PZT (piezoelectric lead zirconate titanate) actuator-driven system, in which an individual piezoelectric transducer serves both as a sensor and an actuator simultaneously when a PZT patch is attached to or embedded inside the host structure [7]. Because the admittance signature of a PZT patch is expressed as a coupling of the mechanical impedance of the transducer and the mechanical impedance of the host structure. Any changes in the mechanical impedance of the host structure involved with changes in structural material properties, structural configuration or boundary conditions caused by structural damages are reflected in the admittance measurement [8]. Hence, the changes in the admittance signature, which is the inverse measure of mechanical impedance of the host structure, are indicative of the presence of structural damages.

Assuming that the PZT patch is a bar undergoing one-extensional actuation (axial vibrations) in the length direction under a harmonic electric field, and the structure is a single degree of freedom of spring–mass–damper system, most practical application of EMI technique were based on this one-dimensional EMI model proposed by Liang et al. [7]. To consider the 2D effects associated with PZT vibrations, Zhou et al. [9] developed a coupled electromechanical admittance for a generic PZT actuator driven two-dimensional structure. Based on the concept of 'effective impedance', Bhalla et al. [10] extended the model of actuation of the PZT patch from uni-extensional in length direction only to bi-extensional actuation in the length and the width directions. However, the major limitation of these models is that they ignore vibration of the PZT patch in the thickness direction. Actually, the actuations of the PZT transducers can be divided into extensional (along the length and width directions), longitudinal (along the thickness direction) and shear actuations. Considering the thickness vibration and its applicability to embeddable structures, Annamdas et al. [8] presented an embedded piezo-impedance patch and its interaction with the host sandwiched beam using length actuation and thickness actuation of the PZT patch. Subsequently, they also examined the three-dimensional interaction of a transducer with the host structure based on the concept of the directional sum impedance formulation [11–13]. These models more accurately considers both the extensional and longitudinal actuations, along with the mass of the transducer, however, the formulation of the complex admittance of the PZT patch are depended on the experimental trial-and-error test, which is complicated and prohibit their direct application in practice.

Conventionally, surface-bonded PZT active sensors are often utilized in the EMI technique to measure admittance. For instance, Sun et al. [14] firstly applied the technique to an assembled truss structure. Then Soh et al. [1] investigated the feasibility of PZT patch for damage detection on a RC bridge. Bhalla et al. [3] diagnosed damage on a model reinforced concrete frame subjected to base vibrations on a shaking table. Tawie et al. [15] extended the surface-bonded PZT patch to monitor the strength gain of concrete. Min et al. [16] detected real damage on a lab-scale pipe structure and in a full-scale bridge through impedance-based method. In consideration of the vulnerability and fugitiveness of PZT sensors, some researchers utilized embedded PZT sensors instead of surface-bonded ones. Gu et al. [17] embedded the PZT transducers as the form of 'smart aggregates' into concrete to monitor the strength development of concrete structures. Annamdas et al. [13] investigated the effectiveness of embedded PZT transducers to monitor the curing process and damage severity of concrete structures. Talakokula and Bhalla [18] compared the sensitive capabilities of surface bonded and embedded piezoceramic patches in diagnosing chloride-induced corrosion for reinforced concrete structures. Zuo et al. [19] and Wang et al. [20] proposed two different 3D dimensional models for concrete strength gain monitoring. More recently, Kaur and Bhalla [21] provided an experimental research of achieving both energy harvesting and structural health monitoring from the same PZT patch in the form of concrete vibration sensor (CVS) for RC structures, which showed a harvesting potential of vibration energy for embedded CVS. Talakokula et al. [22] effectively applied embedded piezo sensors for reinforcement corrosion assessment of RC structures and extracted equivalent structural parameters for damage evaluation. These studies generally utilizing embedded-PZT sensors to monitor structure had satisfying results because PZT active sensors were much nearer to structural inner property variations, which directly affects the mechanical behavior of PZT patch such as boundary constraints.

So far, the effectiveness of embedded PZT sensor for non-destructive evaluation on structural damage has not been systematically studied. The objective of this paper is to validate the sensitivity of embedded PZT sensor for structural impact damage detection. Firstly, this study proposed a new embedded two-dimensional model characterizes the interaction between an embedded square PZT transducer and the host structure. It is based on the concept of 'effective impedance' and does not depend on any indeterminate parameters, which has a more concise formulation of the complex admittance and validates by experimental results. Thus wherever possible, it can protect the active PZT sensors from external load or impact, vandalism and environmental disturbance, which avoids fragility and fugitiveness of PZT patch. The sensitivity of the embedded active PZT sensors in practical application was then investigated in the experiment of detecting impact damage on a concrete beam, through comparison with the surface-bonded PZT patches. The validity of embedded PZT sensor in quantification of structural damage was investigated by using slope-based root mean square deviation (RMSD) index, a new baseline-changeable RMSD index was also proposed to evaluate the impact effect for the two types of active PZT sensors. Finally, concluding remarks were summarized.

2. Effective mechanical impedance in EMI technique

For the harmonic interaction between an active PZT sensor and the host structure, the mechanical impedance of the structure at the point of the applied force is defined as the ratio of the driving harmonic force to the resulting harmonic velocity at that point. Where a harmonic force $F(t)$ and the resulting harmonic velocity can be expressed as:

$$F(t) = F_0 cos\omega t + jF_0 sin\omega t = F_0 e^{j\omega t} \tag{1}$$

$$\dot{u} = \dot{u}_0 e^{j(\omega t - \phi)} \tag{2}$$

where ϕ is the phase angle lagged behind the force caused by the "mechanical impedance" of the structure at the driving point, which can be denoted as:

$$Z = \frac{F}{\dot{u}} = \frac{F_0}{\dot{u}_0} e^{j\phi} \tag{3}$$

Conventionally, the definition of mechanical impedance Z is referred to the PZT end point connected with the host structure. However, according to Bhalla et al. [10], the mechanical interaction between the patch and the host structure is not restricted at the PZT end points and it extends all over the finite sized PZT patch. When a finite sized square PZT patch bonded to or embedded inside a structure is subjected to a spatially uniform electric field, it undergoes harmonic vibration. Assuming that PZT patch is infinitesimally small as compared to the host structure, so it possesses negligible mass and stiffness. And regarding the interaction