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Mechanical impedance based embedded piezoelectric transducer for reinforced concrete structural impact damage detection: A comparative study

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HIGHLIGHTS

- Effective structural mechanical impedance (ESMI) based method was proposed.
- Structural mechanical impedance (SMI) based method was briefly introduced.
- Admittance signatures were measured in testing a reinforced concrete (RC) beam.
- Comparative study was conducted among admittance, SMI and ESMI signatures.

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ABSTRACT

Electromechanical admittance (inverse of impedance) based nondestructive evaluation method has been extensively applied to damage detection and health monitoring of engineering structures. This paper proposed an innovative method of using the effective structural mechanical impedance (ESMI) to detect reinforced concrete (RC) structural damages. ESMI based method was first formulated based on a generic two-dimensional model for embedded piezoelectric (PZT) transducer interacting with a host structure. And structural mechanical impedance (SMI) based method using a typical one-dimensional PZT-structure interaction model was also briefly introduced. Validation of the proposed method was investigated in an experiment of testing a RC beam structure with different levels of impact damages, in which raw admittance signatures measured from three embedded PZT transducers were used for extracting ESMI and SMI signatures. Sensitivity of ESMI, SMI and admittance signatures was then qualitatively compared in detecting RC beam structural damages. Additionally, these three signatures based damage quantification was also conducted using two-types of statistical root mean square deviation (RMSD) indices. Results demonstrated that the ESMI signature exhibits well performance in detecting the RC beam structural impact damage. The proposed method provides a promising alternative for precise prediction of RC structural damage especially when the PZT transducers embedded inside structures.

1. Introduction

Reinforced concrete (RC) structural damages initiated from construction deficiency, earthquake excitation or external impact are deteriorated with material aging, cyclic loading and environmental erosion in their service life, which goes against favorable operations and increases risk to catastrophic collapse of RC structures. Recent developments of various real-time and in-situ structural health monitoring (SHM) and nondestructive evaluation methods have provided powerful tools to help ensure structural safety and prevent their premature failures. Among a diversity of SHM approaches, using intelligent piezoelectric materials such as piezoelectric lead zirconate titanate (PZT) referred as electromechanical impedance technique has shown a promising potential and provided a variety of successful applications in civil engineering fields over the past two decades, due to its merits of free model, fast response, high sensitivity and economical cost [1–6].

In the electromechanical impedance technique, PZT patch is simultaneously served as both sensor and actuator, as it possesses the direct and inverse effects that are electrical charges produced in response to an applied strain field and conversely mechanical

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strain produced in response to an applied electric field [7]. When a PZT patch surface-bonded onto or embedded inside a host structure, measuring its electrical admittance or inverse impedance at the pristine and damaged states constitutes the basis of the impedance technique for SHM. Since electrical admittance directly characterizes the electromechanical property of the PZT patch coupled with the mechanical impedance of a host structure, any changes in structural mass, stiffness or damping caused by damage thus reversely impact the mechanical impedance and reflect in admittance signature. In this way, structural damage is recognized as lateral and vertical shifts of admittance signature [8,9]. Commonly used one-dimensional model of PZT-structure interaction system deemed the PZT patch as a thin bar undergoing axial harmonic vibration in one direction [10], which associated the mechanical impedance of structure with the formulation of electromechanical admittance. Zhou et al. [11] extended the one-dimensional model to a generic two-dimensional one by considering the vibrations of the PZT patch on a planar structure. Simplified two-dimensional model based on the concept of 'effective impedance' was then presented by Bhalla and Soh [12], in which PZT actuation in length direction was extended to bi-extensional actuations in the length and width directions. More accurately, both one and two-dimensional simplified impedance models to incorporate shear lag effect into admittance formulations were developed [13,14]. These models generally ignored the vibration of the PZT transducer in the thickness direction, thus better fitted for dynamic description of surface-mounted PZT patches. To describe the vibrations in the length and thickness direction of PZT transducer, modelling for embedded PZT patch interacted with a sandwiched beam was formulated by Annamdas and Soh [15]. Additionally, three-dimensional PZT-structure interaction models were also developed based on the concept of directional sum impedance, which effectively eliminated the restrictions of the PZT shape, size, and isotropy on the previous models [16,17]. However, admittance formulations in these models depending on the experimental trial-and-error test are rather complex for extracting structural impedance information in practice.

Traditionally, raw signatures measured from the PZT transducer including conductance (real admittance), susceptance (imaginary admittance), voltage responses, and wave energy are directly used for RC structural damage analysis. Soh et al. [18] reported the 'smartness' of PZT transducer in detecting damage of a RC bridge structure and concluded that conductance of the PZT transducers located in the vicinity of the damage had drastic changes, while those farther away were less affected. Park et al. [19] used impedance signature of PZT patches array to monitor multiple cracks occurred in a RC beam under a third point bending test. Except damage detection [5,6], strength gain monitoring of concrete specimens has been also investigated in [20–25], it has been found that the change in impedance resonance spectra over time was an effective indicator of the hardening of concrete during the curing process. Considering the fragility of surface-bonded PZT patch, it is also embedded inside the RC structures to recognize their property variations. Song et al. [26] embedded PZT patch as smart aggregates for monitoring a RC bridge bent-cap, damage indices based on sensor voltage was found sensitive to the existence and growth of structural cracks. In addition, harmonic amplitude and conductance variation based smart aggregates were also extended to monitor the strength development of RC structures [27,28]. Tawie and Lee [29] also embedded a PZT patch inside concrete to monitor material hydration. Recently, Kaur and Bhalla [30] provided an experimental research of achieving both energy harvesting and SHM from a same PZT patch in the form of concrete vibration sensor (CVS) for RC structures, which showed a harvesting potential of vibration energy. Similar kind of embedded CVS was also used to detect and locate incipient to severe damages [31]. Karayannis et al. [32] presented an experimental study for damage assessment of concrete reinforcing bars using embedded PZT transducers, admittance signatures was found a clear gradation of the examined damage levels. Voutetaki et al. [33] compared voltage responses of both bonded and embedded PZT transducers in shear-critical RC beams structural damage indication and presented promising results in the prediction of the forthcoming final shear failures. Recently, time domain responses from PZT transducers integrated with singular value decomposition were developed to evaluate truss bridge damages [34], monitoring the dynamic normal stress of concrete cylinder specimens [35], RC beam cracking damages were also investigated by using embedded PZT transducers [36,37].

However, raw signature from PZT transducer not only couples structural property but also include that of PZT transducer, which is susceptible to ambient impact induced damage [38,39]. To realize more direct structural damage evaluation, Bhalla and Soh [40] proposed a complex damage metric contains structural stiffness, mass, and damping to diagnose damage on a modelling RC frame subjected to base vibrations, it has been found that the methodology performed better than the low-frequency vibration methods. Yang et al. [41] extracted structural mechanical impedance (SMI) from admittance signatures for determining the sensitive range of a PZT sensor on a two-story concrete frame subjected to base vibrations. Talakokula et al. [42,43] applied embedded piezo sensors for reinforcement corrosion assessment of RC structures and extracted equivalent structural parameters for damage evaluation. Wang et al. [44] used the effective mechanical admittance signature calculated from three-dimensional embedded PZT impedance model to monitor concrete strength development. In our previous work [45], a two-dimensional embedded PZT-structure coupling model was theoretically formulated and validated through experimental study. It has been found that the embedded PZT sensor was sensitive to RC structural impact damage and less susceptible to external impact than surface-bonded ones. So far, the feasibility of effective structural mechanical impedance (ESMI) has not been systematically studied in SHM applications.

In this paper, a comparative study of using raw electromechanical admittance, SMI and ESMI signatures is made for accurate evaluation of RC structural damages. First of all, a previously proposed model in our previous work [45] is developed to a more generic one which fits for characterizing an embedded PZT transducer and imposes no limitation on PZT shape, size, and isotropy. Computation process for extracting the ESMI signature is then theoretically derived. As comparisons, SMI signature is also derived from the admittance signatures based on a typical one-dimensional PZT-structure interaction model. The proposed ESMI-based method is then applied to an experimental study of detecting damage on a RC beam which is damaged by successively knocking off concrete covers. Three types of signatures based root mean square deviation (RMSD) indices are additively computed for damage quantification. Concluding remarks are finally summarized.

2. Electromechanical impedance models

In the application of electromechanical impedance technique, one PZT patch is generally preliminary surface-bonded to or embedded inside RC specimens. When the PZT patch is stimulated by an applied voltage signal, mechanical strain would be correspondingly produced due to the converse piezoelectric effect. Mechanical vibration is then transferred to the host structure. As a results, structural response as mechanical strain would be conversely transferred to the PZT patch as an electrical signal due to the direct piezoelectric effect. This kind of electrical signal is admittance or converse impedance consisting of the conductance (real part) and the susceptance (imaginary part), which is recorded