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Understanding the coupled electromechanical response of a PZT patch attached to concrete: Influence of substrate size

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ABSTRACT

The influence of the substrate size on the coupled dynamic electromechanical (EM) response of a PZT (Lead Zirconate Titanate) patch attached to a concrete substrate and the scaling of the response with size are investigated using an approach which combines experimentation with numerical simulations. The dynamic response of the PZT patch is investigated for an applied electrical potential, which is applied at multiple frequencies. The electrical conductance spectrum of the bonded PZT patch contains narrow, closely-spaced, local peaks, which exhibit dependence on the size of the substrate. The closely spaced peaks in the electrical conductance response of a PZT patch bonded to a concrete cube are identified with the structural modes of the cube. The local peaks are superimposed over the baseline EM response of the bonded PZT patch. The resonant behavior of the bonded PZT patch is identified in the baseline EM response, which is determined by the dimensions of the PZT patch, its elastic material properties and the stiffness of the substrate medium. The dynamic response of a PZT patch attached to a finite-sized substrate is influenced by the mechanical impedance to its motion arising from the structural motion of the cube and the dynamic impedance offered by the substrate material. As the size of the concrete substrate increases, the structural peaks are damped and diminish in amplitude relative to the amplitude of the resonant peaks of the bonded PZT patch. For each resonant mode of the bonded PZT patch in the electrical conductance spectrum, there is a finite zone of influence beyond which the influence of the boundary is insignificant. The zone of influence is smaller for PZT resonant modes of higher frequency. For physical dimensions of the substrate smaller than the zone of influence of the resonant mode, the structural modes of the substrate are superimposed on the resonant mode of the bonded PZT patch.

1. Introduction

PZT patches are increasingly being used in health monitoring schemes and in developing damage detection strategies for structural components. The use of a PZT patch to infer about the level of damage in the substrate requires interpreting the coupled electro-mechanical (EM) response of the PZT patch attached to the substrate. When a PZT patch is attached to a substrate, the dynamic motion of the PZT patch in response to an applied electrical potential depends on the dynamic mechanical impedance to its motion provided by the substrate. Most experimental studies on the coupled EM response of PZT patches attached to a concrete substrate involve using laboratory-sized specimens Ayres et al. [2], Dongyu et al. [6], Hu et al. [21], Xu et al. [25], Narayanan and Subramaniam [12,13], Liang et al. [24], Lim et al. [22], Liu et al. [23], Narayanan et al. [28]. Application of these results to real structures requires a careful evaluation of the influence of geometry and size of the specimen on the dynamic mechanical impedance provided to the motion of the PZT patch. Separating the influence of the geometry and the finite size of the substrate from the mechanical impedance of the substrate material is essential for developing EM impedance-based damage detection procedures suitable for structural applications.

The electrical admittance (or impedance) spectrum of a PZT patch, which is obtained by varying the frequency of the electrical input depends on the coupled electro-mechanical (EM) response of the PZT patch to the given electrical input subjected to the dynamic restraint to its motion from the substrate. Most approaches for predicting the dynamic response of a coupled PZT patch subjected to a given electrical input idealize the dynamic restraint as the mechanical impedance of the substrate derived from a single or a multi-degree of freedom system Liang et al. [10], Bhalla and Soh [3], Xu and Liu [17], Yang et al. [19], Song et al. [29], Wang et al. [26], Ribolla et al. [27]. This method provides a reasonable approximation for the coupled electro-mechanical response of a PZT attached to a structure where the energy supplied by the motion of the PZT patch is sufficient to excite structural motion or to represent the dynamic impedance of the substrate over a narrow range of frequencies. The approach of representing resistance to the

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Nomenclature

l	length of the PZT
b	width of the PZT
t	thickness of the PZT
S	strain vector
T	stress vector
C_E	elasticity matrix
d^T	piezoelectric coefficients
E	applied electric field vector
D	electric displacement vector
ε_T	dielectric permittivity
e	relative permittivity
ν	Poisson's ratio of the PZT
ρ	density of the PZT
δ	dielectric loss factor of the PZT
ζ	damping ratio of the PZT
Q_m	mechanical quality factor
Y	admittance
I	current
V	applied voltage
I_Z	current density along the poling direction of the PZT
$\overline{C_E}$	complex elasticity matrix
$\overline{\varepsilon_T}$	complex dielectric permittivity
j	$\sqrt{-1}$
η_s	isotropic loss factor of the PZT
η	isotropic loss factor of the concrete cube

motion of the PZT patch using the dynamic impedance derived from distinct structural modes associated with a known pattern of structural motion has been applied successfully to thin, light plate-like structures made of aluminum and composites, typically used in aerospace applications Zagrai and Giurgiutiu [20], Xu and Liu [17], Giurgiutiu et al. [8], Bhalla and Soh [4], Yang and Hu [18], Gresil et al. [9], Lim and Soh [11], Kamas et al. [30], Rebillat et al. [31].

A clear understanding of the coupled EM response of a PZT patch attached to a concrete substrate is still evolving. Concrete structural elements typically have a large mass and therefore structural modes of vibration have low frequencies. The energy requirements for exciting structural modes in concrete structures are high. While in previous studies, some low-frequency peaks in the EM response of PZT patches attached to concrete cubes have been reported, the exact nature of these peaks was not clearly established Soh and Bhalla [15], Annamdas and Radhika [1], Narayanan and Subramaniam [32]. The influence of the boundary in finite-sized concrete specimens is not fully understood. Considering the high material damping of concrete, information on the finite zone of influence beyond which the influence of the boundary may be insignificant is not yet available. The contributions of the material of the substrate and the structural motion to the mechanical impedance in the EM response of the PZT attached to a concrete substrate is not fully decoupled.

The objective of this study is to understand the influence of the finite size of a concrete substrate on the electrical impedance measurement of a bonded PZT. The approach followed includes experimentation using different sized concrete cubes and a calibrated numerical model for evaluating the full range of variables including PZT patch size. The experimental investigation establishes the fundamental issue of scaling of response with size. The numerical simulation is performed to provide additional insight into understanding the influence of size of PZT relative to the concrete substrate. From the measured electrical response of PZT patches attached to concrete cubes of different sizes, the baseline response contributed by the mechanical impedance of the material, is extracted. The influence of the finite boundary is shown to be associated with structural resonance modes of the finite sized specimen, which overlap with the baseline resonant response of the bonded PZT patch. From an analysis using the calibrated numerical model, the resonant modes of the bonded PZT patch are evaluated for different sizes of PZT patch. Smaller PZT patches are shown to have resonant modes at higher frequencies in the bonded configuration. A finite-sized zone of influence is identified with each resonant mode of the bonded PZT patch. The zone of influence is smaller for resonant modes of higher frequency. For a size of specimen smaller than the zone of influence of the resonant mode, the structural modes are superimposed on the resonant mode of the PZT patch.

2. Experimental program

The influence of the finite specimen size on the coupled EM response of a PZT patch bonded to a concrete substrate was evaluated using concrete cubes of sizes equal to 40 mm, 70 mm, 100 mm, 150 mm, 200 mm and 250 mm. All the specimens were made from the same batch of concrete and cured under water for 90 days. The elastic properties of concrete measured using three 150 mm cubes are given in Table 1. The average compressive strength of concrete measured from the 150 mm cubes was 63 MPa.

Square PZT patches of 20 mm size and 1 mm thickness were used in the study. The PZT is composed of the two chemical elements lead (Pb) and zirconium (Zr) combined with the chemical compound titanate. The powders of the component metal oxides are mixed in specific proportions then heated to attains a dense crystalline structure. The electrodes are applied to the appropriate surfaces and poled at high electric field and temperature. The PZT material properties are given in Table 2. The electrical admittance measurements were performed on the PZT patches using a 6500B series impedance analyzer of Wayne Kerr make which has a frequency range of 20 Hz–20 MHz with frequency step size of 0.1 mHz and a measurement accuracy of ± 0.05%. In a typical electrical admittance measurement, the electrical admittance of the PZT patch was measured at an applied voltage of 1 V and frequencies varying in the range between 10 kHz and 500 kHz. Measurements were performed at 800 discrete frequencies at a frequency interval of 613.2 Hz. Conductance (real part of admittance) response of the free PZT patch was extracted from the electrical admittance measurements before attaching it to the concrete cube. Typical conductance responses of free PZT patches (before attaching to the concrete substrate), as a function of the frequency of applied electrical input are shown in Fig. 1(a). The resonant behavior obtained from PZT patches used in the experimental study were nominally comparable.

Resonant modes of the free PZT patch can be identified with peaks in the conductance spectra (identified as f_1 through f_6 over the frequency range between 10 kHz and 500 kHz). Each PZT patch was attached to the center of one face of a concrete cube using a two-component epoxy. The epoxy was allowed to cure for one day before initiating measurements. A block of 1 kg mass (9.81 N) was placed on the bonded PZT patches during the curing time to maintain the similar thickness of epoxy among the specimens. The properties of the hardened epoxy are given in Table 1. A schematic figure and a photograph of the experimental test setup for electrical admittance measurements from a PZT patch attached to a concrete cube, are shown in Fig. 2. The conductance signature derived from an electrical admittance

Table 1
Properties of the concrete and epoxy.

Properties	Concrete	Epoxy
Density (kg/m^3)	2380	1250
Young's modulus (GPa)	40	2
Poisson's ratio	0.2	0.36