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Sensitivity Analysis of Bonding and Bonding-free Impedance based Structural Health Monitoring

Kexin Cai[1], Jialin Liu[2], Venu Gopal Madhav Annamdas[3*] and Chee Kiong Soh[4]

[1,2,3,4] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore
([*]annamdas@ntu.edu.sg)

ABSTRACT: Recent decades has seen the rapid development of lead zirconate titanate (PZT) as a smart material in electro mechanical impedance (EMI) based structural health monitoring (SHM) technique. In this technique, the PZT transducer is attached to the host structure either by surface bonding or embedding it inside where it acts as both sensor and actuator when subjected to electro mechanical field to result in a unique electromechanical signal. The attachment of transducer to the host structure is mostly accomplished by using adhesive bonding layers, which affect the sensitivity of the transducers to a great extent. However for effective sensitivity the transducer needs to have proper interaction with the host structure irrespective of whether there is a bonding layer or not for getting interrogating signal which serves as an indication of the structural health. In the recent past, researchers started exploring partial bonding layer or bonding layer free PZT transducer based EMI technique. In these cases, the attachment of transducer to the host structure is not by bonding adhesive but by mechanical means such as a thumb force, contact pressure, nut-bolt etc. These provide alternative strategy where installing transducers becomes a problem. The present paper focuses on the experimental sensitivity analysis of PZT transducers on the host structure using bonding layer free interaction, using magnet supports. The investigations aid the future researchers to explore the options of using bonding free PZT transducers for effective SHM.

1 INTRODUCTION

1.1 Background

Effective structural health monitoring (SHM) is a process to strategically study the structural integrity for detection of incipient damages or stresses and to characterize the health of engineering structure using fully or semi-automatic techniques without disturbing the regular working conditions of a structure. Non-destructive testing (NDT) is a manual process to monitor a specific area of the structure making it render useless during period of monitoring. SHM and NDT are rigorously employed in aerospace, civil and mechanical engineering for saving huge economy and prolonging the structural life.

Electromechanical (EM) impedance (EMI)-based monitoring using piezoelectric (lead zirconate titanate (PZT)) transducers is one such method, which is currently employed as NDT but can be used in future as SHM technique if several issues are thoroughly addressed (Madhav and Soh 2007, Annamdas et al 2010, Annamdas and Soh 2010, Annamdas 2012, Annamdas and Radhika 2013), which can thus make it semi or fully automated technique. This technique results in a frequency domain based health signal which deviate if any defect exists in the structure under investigation. This EMI has been a fast emerging technique for the last few decades in laboratories but rarely adopted in actual practice (Annamdas and Yang 2010).

1.2 Root means square deviation (RMSD)

Many times mere signals do not provide conclusive evidence of structural disintegrate if any. Thus Root means square deviation (RMSD), a statistical approach that describes the change in signal as compared to the initial state, i.e. the healthy state needs to be employed. This RMSD index is given as

$$\mathrm{RMSD}(\%) = \sqrt{\frac{\sum_{i=1}^{N}(G_{i,d}-G_{i,h})^2}{\sum_{i=1}^{N}(G_{i,h})^2}} \times 100\% \quad (1)$$

Where d and h are the conductance signals measured at frequency i, at the damaged and the healthy state respectively.

2 LITERATURE REVIEW

2.1 EMI based NDT technique

Most Monitoring methods are based on the principle that damage could alter the structural mass, stiffness, damping or energy dissipation properties and in-turn revise the dynamic response of the structure (Sohn et al., 2004). Some of the commonly used NDT techniques include visual inspection, radiography, ultrasonic guided wave, and electromagnetic fields. In the recent past, EMI technique has also been considered apart from other NDT techniques in various strain, damage and fatigue failure application of aerospace, mechanical and civil engineering (Park et al 2003, Annamdas and Soh 2010, Annamdas et al 2014).

2.2 Piezoelectric material, an active smart material

Smart materials are active and passive, where active materials are mostly actuators and passive materials are mostly sensors (see section 2.4). However PZT materials are one such active smart material (Annamdas and Annamdas 2009) that behave both as actuator and sensor applications in EMI technique.

In actuator applications, PZT produces voltage when deformation/stress in applied where as it produces deformation when electric field is applied in sensing applications.

2.3 Principles of EMI Technique

EMI technique is based on the EM coupling ability of PZT materials. When subjected to electrical excitation, the PZT patch either surface-bonded on or embedded in the structure will generate localized strain parallel to the structure (Annamdas 2007). The response of the host structure to this excitation could be acquired in the form of electric current that represents dynamic structural stiffness or impedance (Annamdas and Rizzo 2009, Zagrai et al., 2010).

The modulated electric current, in terms of complex electrical admittance (conductance and susceptance) is recorded by the impedance analyzer. Since the electrical admittances carry information pertinent to material properties, structural configuration and boundary conditions of both actuator and host structure, and any damages to the host structure will alter these characters.

Thus admittance (inverse of electrical impedance) can be adopted as an indication of presence of damages in engineering structures under investigation. These admittance signals are collected in a frequency spectrum and it comprises of a series of peaks and valleys at various frequencies, arranged as a signal.

2.4 Application and related issues of using EMI

A – Active/ passive materials for EMI method

Not just the smart materials but even the structures under investigation can be classified into active and passive based on the properties of the structure to be monitored. Structures made from steel and aluminum are active in EMI applications as the interaction between PZT transducer and host structure is more effective. Increase in number and amplitude of structural peaks in the EM admittance signals could be observed as compared to passive structures such as clay and timber (Annamdas and Radhika 2013).

B – Frequency range

In general, the EM admittance signals are usually captured in a wide range of high frequency excitations between 0 to 400 kHz. However it is proposed that the selection of suitable range is based on dimension of specimen and sensitivity. Higher frequency range results in reduced sensitivity. At higher frequencies, sensing region becomes very small and the transducers show adverse sensitivity to bonding conditions or transducer itself rather than the host structure. Thus a usual range of 0 to 150 KHz is preferred as it captures several resonance peaks that are enough to judge the problem in a structure.

C – Bonding method

Other than surface-bonded PZTs, nut-bolt is a semi-embedded method of the PZT to the host structure (Luo et al, 2014). However, this method requires the host structure to be bolted, which is better for concrete, and thus was not considered. We can consider non-permanent bonding methods using thumb force or magnets. However, the change in thumb forces always caused the variations in admittance signals and thus led to the inconsistency of the results as shown in Figure 1(b).

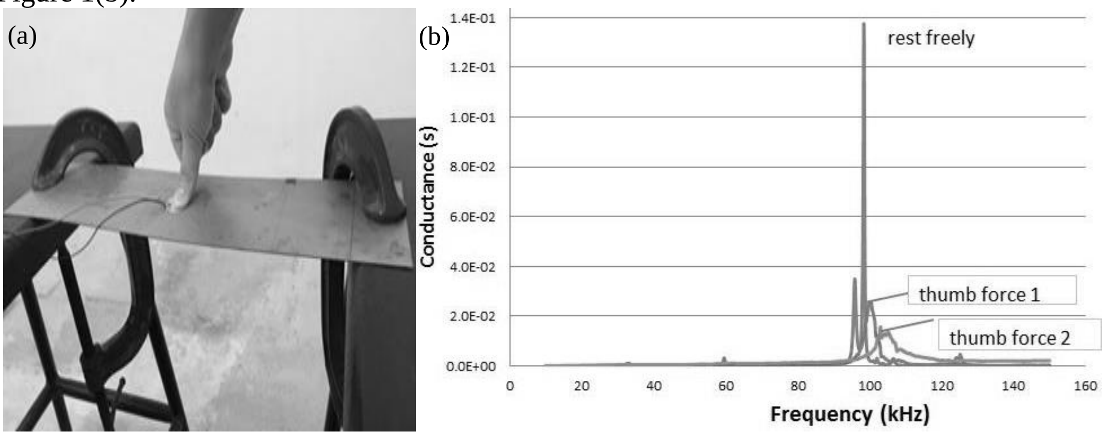

Figure 1. (a) Photo and (b) conductance signals of thumb force bonded PZT

3 EXPERIMENTS AND RESULTS

3.1 Experimental setup

The set-up consisted of a Wayne Kerr precision impedance analyzer, personal computer, data extraction software, a rectangular aluminum specimen (dimensions as shown in Figure 2(b)) which was fixed using G-clamps at 40 mm distance from edges, on two shorter sides as shown in Figure 2(a). Five PZT transducers were surface-bonded using epoxy (designated as surface PZTs) at locations 1 to 5, and a transducer was attached using earth magnets (10mm×10mm x 5 mm) at location M (designated as magnetic PZT). As the host structure was aluminum, one main earth magnet was placed on top of the transducer (placed on specimen) and an identical support magnet was attached below the specimen so as to hold the PZT transducer by pair of top-bottom magnets. Analyzer was tuned to a frequency range of 10 kHz to 150 kHz with an increment step of 0.1 kHz.

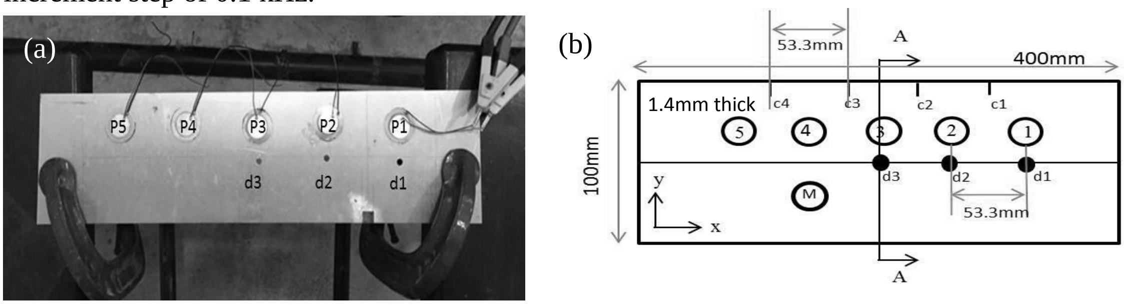

Figure 2. (a)Photo and (b) schematics of specimen with details of 5 surface PZTs and 1 magnetic PZT

3.2 Tests procedures and signal acquisition

A baseline result, i.e. signals of the structure at the healthy state, was first obtained followed by subsequent signals for the following experiments.
a) Damages by drilling: Three holes of the same diameter 5 mm were drilled one after the other along the horizontal centerline of the aluminum plate as shown in Figure 2(b).
b) Crack test: Four cracks of 10 mm length and 1 mm width were made as shown in Figure 2(b).
c) Load test: A progressive load test was carried out at the center of plate (A-A) by suspending weights (0N, 10N, 20N and 30N).
Corresponding responses from host structure, in the form of conductance and susceptance, were recorded for both surface and magnetic PZTs.

3.3 Experimental findings

Since the bonding layer between PZT transducers and the aluminum plate may vary, the baseline results for different PZT transducers were different.

A – Surface PZTs

a. Damages by drilling

Conductance and susceptance signals of PZT transducers 1 to 5 were plotted. It was observed that the peaks in conductance signals shifted when the host structure was subject to damages. A trend of the downward shift of conductance peaks is shown in Figure 3(a).

However for certain frequency ranges, conductance signals were very close and a clear trend of shifting peaks could not be observed; hence the statistical method, i.e. RMSD, was adopted to determine the change in signals as shown in Figure 3(b).
Generally the RMSDs increase with number of holes, indicating that the difference between the damaged and healthy state will enlarge as numbers increase.

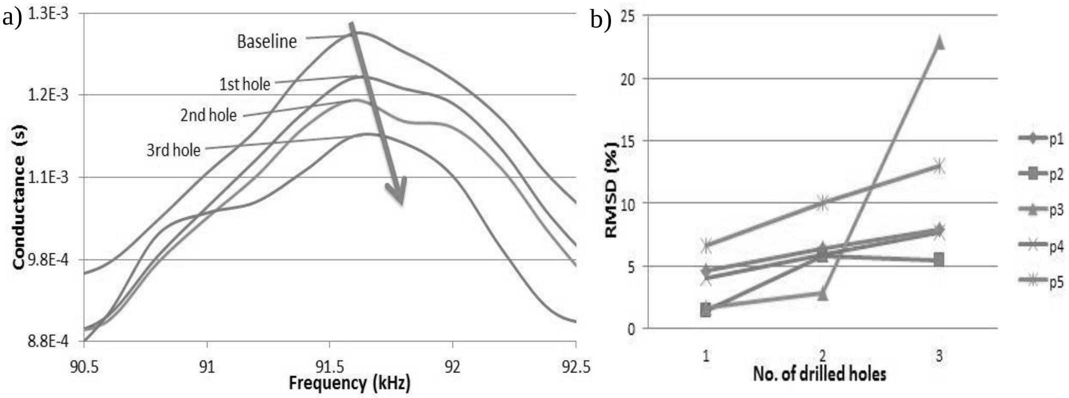

Figure 3.Signal processing (a) Conductance signals of surface PZT 5 (b) Conductance RMSD of surface PZTs – damages by drilling holes

b. Crack test and load test

Similar increasing in RMSD values with increasing cracks and loadings was also seen during the crack test and load test, as shown in Figures 4 (a) and (b) . It could be noticed that the RMSD for most of the cases increases.

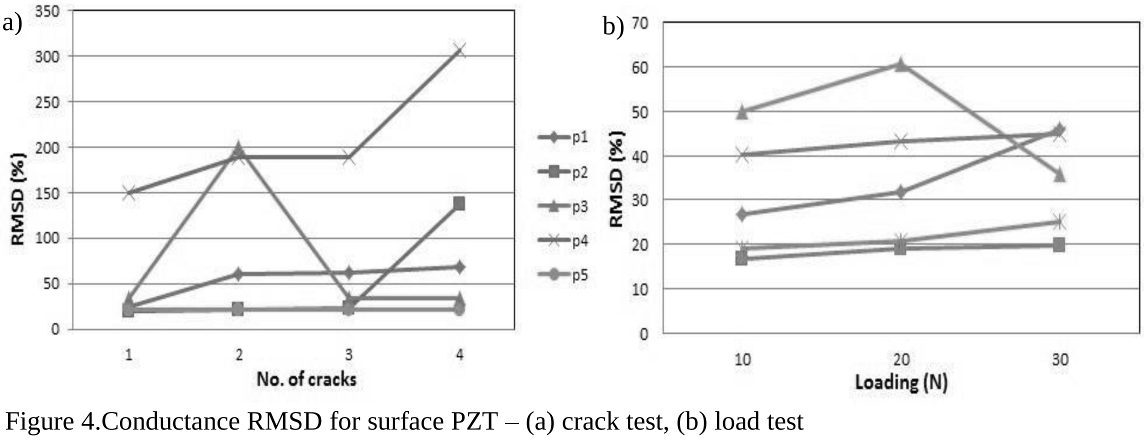

Figure 4.Conductance RMSD for surface PZT – (a) crack test, (b) load test

B – Magnetic PZTs

The conductance signals of magnetic PZT transducer in the test of inducing damages by drilling holes and cracks show a consistent trend of downward peak shifting, which is similar to surface PZTs. Figure 5(a) shows a downward shift of conductance peaks with increasing loadings. RMSD values for both surface and magnetic PZTs (as shown in Figure 5(b)) increased with propagation of damages and loads.

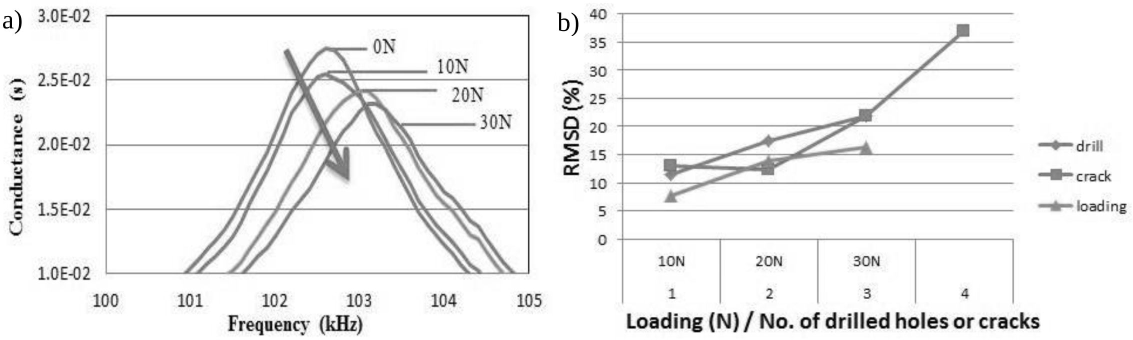

Figure 5.Signal processing (a) Conductance signals of magnetic PZT (b) Conductance RMSD of magnetic PZT – damages by drilling holes, crack and load test

3.4 Numerical Modeling

Numerical modeling in ANSYS was conducted to verify experimental findings. Half of the PZT – structure model with the same dimensions and boundary conditions as the experimental set-up was created in ANSYS, with applied loading from 0N to 30N as shown in Figure 6(a). However, an upward shifting of conductance peaks is shown in Figure 6(b), which is opposite to the shifting trend in experimental findings was observed. The difference between the numerical result and its experimental counterpart might be due to the idealization of bonding layer in the modeling, which will affect the admittance signals of the PZT (Yang et al, 2008).

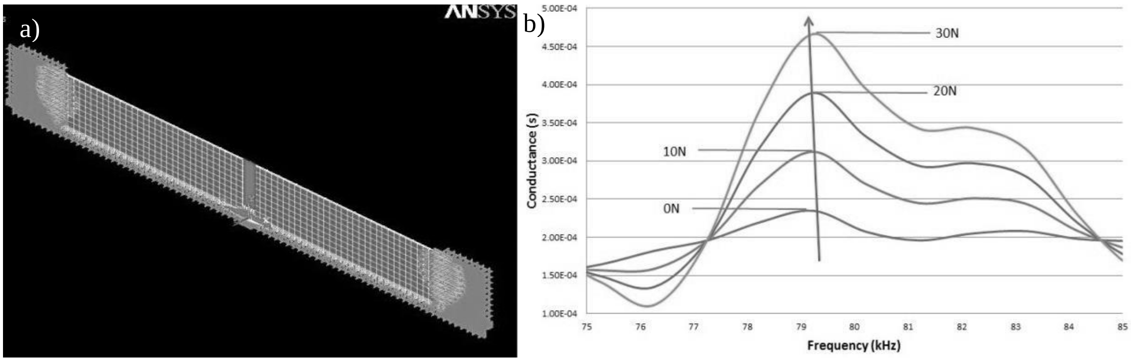

Figure 6.Load test – (a) Numerical screenshot of the model (b) Numerical conductance signals

4 CONCLUSIONS

Compared to visual inspection of the shifting of conductance peaks of PZT transducers, RMSD is a more reliable way to determine the sensitivity of PZT transducers to damages and loads. Besides, different bonding conditions will affect the shifting of signals when subjected to damages and loads. Thus, several bonding layer free methods of installing the PZT were proposed. Among those, magnetic PZT showed the ability to effectively reflect the structure's responses when subjected to damages and loads. Future research could be focused on improving the modeling of the bonding layer in the numerical analysis of PZT – structure interaction, to obtain a more comparable result to its experimental counterpart, so as to help in the prognosis of structural damages.

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