This is the accepted version of the publication Kaur N, Li L, Bhalla S, Xia Y. A low-cost version of electro-mechanical impedance technique for damage detection in reinforced concrete structures using multiple piezo configurations. Advances in Structural Engineering. 2017;20(8):1247-1254. Copyright © The Author(s) 2016. DOI: 10.1177/1369433216677124

# A LOW-COST VERSION OF EMI TECHNIQUE FOR DAMAGE DETECTION IN RC STRUCTURES USING MULTIPLE PIEZO CONFIGURATIONS

**Naveet Kaur[1, 2], Lingfang Li[2,*], Suresh Bhalla[3] and Yong Xia[2]**

[1]Bridge Engineering and Structures Division, Central Road Research Institute, 110025, New Delhi, India

[2]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[3]Department of Civil Engineering, Indian Institute of Technology Delhi, 110016, New Delhi, India

**Abstract:** The electro-mechanical impedance (EMI) technique has developed rapidly during the past few decades as a reliable health monitoring component of civil structures. However, the high cost of impedance analyzer/ LCR meter conventionally used for data acquisition in the EMI technique restricts its wide use in real applications. This paper provides a comprehensive study of exploring the low-cost EMI technique for health monitoring of concrete under destructive testing using multiple piezo configurations. The experimental scheme ensures separate acquisition of both the real as well as the imaginary components of the EMI signature for detailed analysis, a feature not available in some previous low-cost adaptations. The piezo configurations covered here for comparison are the surface-bonded piezo configuration (SPC), the embedded piezo configuration (EPC) and the metal wire piezo configuration (MWPC). The repeatability of the proposed low-cost EMI technique is checked and the results are compared with the traditional counterpart utilizing conventional LCR meter. The two EMI approaches show similar trends of the conductance signature for all configurations. In particular, the MWPC can be adopted as an excellent alternative in practice for reinforced concrete (RC) structures when the direct surface bonding is not feasible. Overall, the low-cost version of the EMI technique is effective to detect the presence of the damage.

**Keywords**: Metal wire, electro-mechanical impedance (EMI) technique, embedded piezo, Concrete Vibration Sensor (CVS), RC structures, low-cost EMI technique

---

* Corresponding author. Email address: lingfang.li@connect.polyu.hk; Fax: (852)2334-6389; Tel: (852)6816-0156

## INTRODUCTION

Recently structural health monitoring (SHM) is increasingly being implemented on large-scale structures (Ni et al., 2012; Xia et al., 2013, 2014). Piezoelectric materials have long been explored as active health monitoring components of civil structures. Several techniques encompassing piezoelectric materials were developed in quick succession during the past few decades, notable among them is the electro-mechanical impedance (EMI) technique. The transducers used in the EMI technique are patches made of piezoelectric materials like lead zirconate titatnate (PZT). When mechanical stress/strain is applied on them, a corresponding voltage is generated and conversely, when a voltage is applied to them, a corresponding mechanical strain is generated. In this way, they can act as both actuators and sensors. In the EMI technique, a PZT patch bonded to a structure is subjected to an alternating voltage excitation through a conventional impedance analyzer/ LCR meter so as to act as an actuator, sweeping through a particular frequency range, generally a subset of 30~400 kHz. Acting as a sensor, the patch acquires an electro-mechanical admittance signature, consisting of the real (conductance, *G*) and the imaginary (susceptance, *B*) components. Owing to ultrasonic frequencies, the EMI technique has higher sensitivity to the incipient damage levels. The different configurations of the piezo sensors which have gained wide acceptance and used for the EMI technique in this paper are discussed as follows.

*Surface-bonded Piezo Configuration* (SPC) as illustrated in Figure 1, is the conventionally employed transducer configuration in the EMI technique wherein a single PZT patch, surface bonded on the host structure, acts as sensor and actuator simultaneously. Using the generic derivation by Liang *et al*. (1994), the complex electro-mechanical admittance $\overline{Y}$ (inverse of electrical impedance) of the coupled system can be further divided into two parts: active admittance $\left(\overline{Y_A}\right)$ and passive admittance $\left(\overline{Y_P}\right)$, according to whether the parameters depend on the properties of the PZT patch alone or on the properties of both the PZT patch and the structure, that is (Bhalla, 2004),

$$\overline{Y} = \overline{Y_P} + \overline{Y_A} \tag{1}$$

where $\overline{Y_P}$ and $\overline{Y_A}$ have the following expressions:

$$\overline{Y_P} = 2\omega j \frac{wl}{h}\left[\overline{\varepsilon_{33}^T} - d_{31}^2 \overline{Y^E}\right] \tag{2}$$

$$\overline{Y_A} = 2\omega j \frac{wl}{h}\left[\left(\frac{Z_a}{Z + Z_a}\right) d_{31}^2 \overline{Y^E} \left(\frac{\tan \kappa l}{\kappa l}\right)\right] \tag{3}$$

where $l$ is the half-length, $w$ the width and $h$ the thickness of the PZT patch. $d_{31}$ is the piezoelectric strain coefficient, $\overline{Y^E}$ the complex Young's modulus of the PZT patch at constant electric field, $\overline{\varepsilon_{33}^T}$ the complex electric permittivity of the PZT material at constant stress, $Z$ the mechanical impedance of the structural system, $Z_a$ the mechanical impedance of the actuator, i.e., the PZT patch, $\omega$ the angular frequency and $\kappa$ the wave number, given by $\kappa = \omega\sqrt{\rho / \overline{Y^E}}$, $\rho$ being the density of the PZT material. Any change in the structural parameters, i.e., the stiffness, the damping and the mass will alter the structural mechanical impedance $Z$ in Eqn (3) and hence, it serves as an indicator of the change in the health state of the structure. Measuring $Z$ directly may not be feasible practically, but $\overline{Y}$ can be easily measured by using an electrical impedance analyzer/ LCR meter. SPC has widely been used in the EMI technique for SHM (Giurgiutiu *et al.*, 2002; Lim *et al.*, 2006; Yang *et al.*, 2007; Bhalla *et al.*, 2009).

*Embedded Piezo Configuration* (EPC) is based on the use of Concrete Vibration Sensor (CVS), embedded in the host structure as shown in Figures 1. As SPC is fragile and usually exposed to the harsh environment, it is easy to get tampered during the operation of the host structure. Hence, embedded CVS, which uses packaged PZT sensor, is more suitable for the health monitoring of reinforced concrete (RC) structures. CVS is composite in nature, has better compatibility with the surrounding concrete, and can withstand the harsh conditions typically encountered in the RC structures during casting. It consists of a PZT sensor patch encapsulated in a proprietary configuration suitable for casting along with the structure, thereby permanently embedding the patch in the host RC structure. Talakokula *et al* (2014) and Talakokula and Bhalla (2014a) have rigorously used EPC for monitoring rebar corrosion in RC structures via the EMI technique. The co-authors have also extensively used EPC for monitoring damage in the RC structures (Kaur and Bhalla, 2015; Kaur *et al*., 2015).

*Metal Wire Piezo Configuration* (MWPC) is based on the use of a PZT patch surface bonded on one end of a thin aluminum wire or foil with the other end of the metal wire/ foil attached to the host structure as shown in Figure 1. Despite several advantages of SPC, its fragile nature renders it unsuitable for the host structures with complex geometry, curved surface and hazardous conditions such as high temperatures and structures under impact. Other practical concerns with SPC are suppressed peaks in the case of concrete structures due to large damping. This results in lack of quick damage related inferences, which can otherwise be drawn from the prominent change in peak frequencies and their magnitude in the conductance signature in metallic structures. To address the aforementioned issues, Na and Lee (2013) proposed the MWPC. Though the sensitivity of this configuration gets lowered, it proves to be a good alternative for structures with complex geometry or hazardous situations where employing traditional SPC becomes cumbersome. Upon excitation, a stationary wave is generated by the PZT patch in MWPC, which further travels to the structure via the metal wire. Any change in the structural parameters due to damage affects the reflected wave, thus altering the admittance signature and allowing the damage detection (Naskar and Bhalla, 2015).

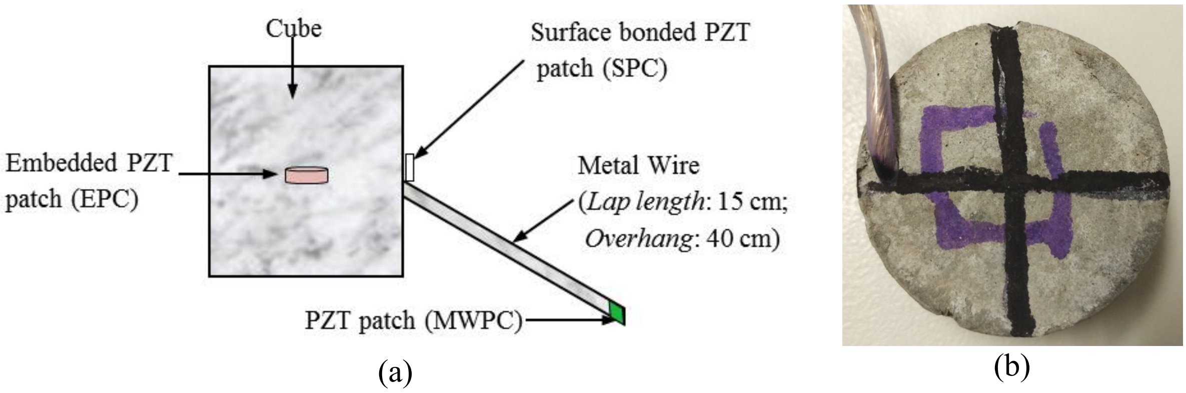



**Figure 1**: (a) Schematic diagram of Cube showing three piezo configurations and (b) Concrete Vibration Sensor (CVS).

**LOW-COST EMI TECHNIQUE**

A low-cost alternative for EMI technique, which otherwise employs an impedance analyser/ LCR meter typically costing USD 20,000 to 40,000, was proposed by Peairs *et al*. (2004). The simple circuit employed by Peairs and coworkers consisted of a small resistance (typically <10 Ω), connected in series with the PZT patch (bonded to the structure to be monitored), as shown in Figure 2. This low-cost alternative has already been demonstrated using SPC for lab sized aluminum specimen in literature (Panigrahi *et al*., 2010). The overall cost of the equipment involved was approximately USD 8000. Later, Bhalla *et al.* (2009) proposed another system with still lower cost of about USD 2000. It utilized Agilent 34411A digital multimeter and a very basic function generator. However, the system was limited in the sense that it only provided measurement of the magnitude of admittance and not the phase. The present study presents a still cheaper alternative hardware configuration and explores its suitability for measurement of admittance for EPC and MWPC in addition to SPC for concrete structures.

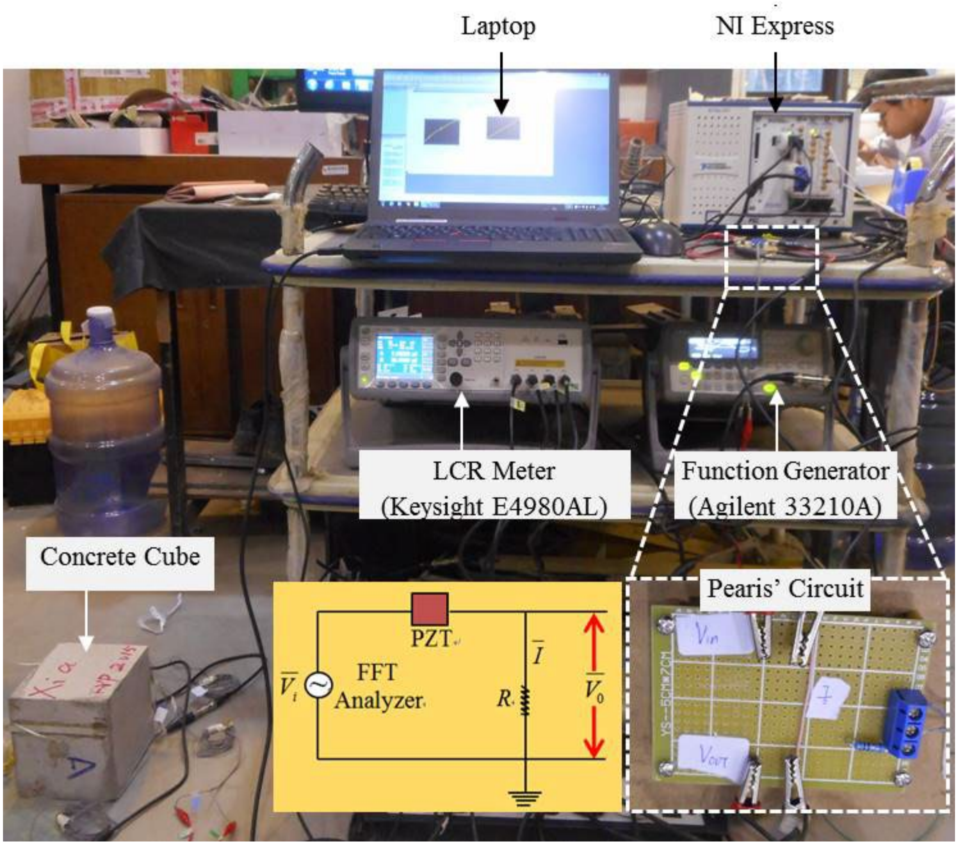



**Figure 2**: Complete experimental setup: conventional LCR meter and Peairs' Circuit (Peairs *et al*., 2004) used for low-cost EMI technique.

As per original configuration of Peairs and coworkers (Figure 2), upon applying an input sinusoidal voltage $\overline{V}_i$ across the combination through the FFT analyzer or equivalent voltage source, the technique essentially involves measuring $\overline{V}_o$ , the output voltage across the sensing resistor R. Assuming that the PZT patch has infinitely large electrical impedance as compared to that of the resistor R, the coupled electro-mechanical admittance $\overline{Y}$ of the bonded patch can be expressed as:

$$\overline{Y} \approx \frac{\overline{I}}{\overline{V}_i} = \frac{\overline{V}_o}{R\overline{V}_i} \tag{4}$$

Though the FFT analysis based approach is very cost-effective, it compromises on damage sensitivity as compared to an impedance analyzer as the latter makes a truly stepwise measurement at each frequency of the prescribed range. It is also important to mention here that this technique cannot achieve the same level of measurement accuracy and repeatability as the LCR based approach, because the latter has sophisticated noise reduction and/or signal pre-amplifying electronics (Song *et. al*., 2013).

The modified low-cost technique proposed in this paper is essentially an extension of the technique proposed by Panigrahi *et al*. (2010). The proposed hardware configuration enhances the sensitivity and is at the same time more cost effective. Referring to Figure 2, a function generator is employed to generate the voltage signal $\overline{V_i}$ replacing the FFT analyzer. However, unlike previous approach (Peairs *et al*., 2004), it uses pure tones of sine waves of gradually increasing frequencies. The output voltage $\overline{V_o}$ at each excitation frequency and its phase lag with respect to $\overline{V_i}$ are measured using NI Chasis Express and hence, resulting in complex admittance function, much like the measurement of the impedance analyzer. This was lacking in the USD 2000 costing configuration proposed by Bhalla *et al*. (2009). In addition, in the proposed approach, the frequency of the imposed signal incrementally varied with each measurement conducted under steady-state condition, much like the sweep mode available in impedance analyzers/LCR meters. This not only ensures higher measurement accuracy, but also eliminates bandwidth restrictions as encountered by Peairs and co-workers (2004).

## EXPERIMENT DETAILS

A series of experiments were carried out in the laboratory with the different piezo configurations described earlier on two concrete cubes (size 150×150×150 mm$^3$, grade M30), as shown in Figures 1 and 2. After the cubes were cast, one raw PZT patch was surface bonded on one face of the cube, denoted by SPC. Right next to the SPC, an aluminum wire was attached using two-part Araldite epoxy adhesive. At the other end of the metal wire, another PZT patch was bonded, which acted as MWPC. The technical details of the PZT patches (including the patches in the CVS) are listed in Table 1. The admittance signature using E4980AL LCR meter was acquired in the range of 50~70 kHz with 100 Hz interval as the benchmark, against which the signatures of the low-cost setup were evaluated. The complete experimental setup for the low-cost technique consisted of the NI Chassis, model NI PXIe1071 with NI PXI 5105 Card and a function generator, model 33210A. The frequency of the function generator was adjusted manually from 50 kHz to 70 kHz at a step interval of 1 kHz.

**Table 1**: Properties of PZT patches and CVSs

| Property | Unit | Value |
|---|---|---|
| Raw PZT Size, $l \times w$ | m×m | 0.01× 0.01 |
| Raw PZT Thickness, $h$ | m | $2.0 \times 10^{-4}$ |
| CVS Diameter | m | 0.03 |
| CVS Thickness | m | 0.02 |
| Piezoelectric Strain Coefficient, $d_{31}$ | m/V | $2.100 \times 10^{-10}$ |
| Young's Modulus, $Y^E$ | N/m$^2$ | $6.667 \times 10^{10}$ |
| Electric Permittivity, $\varepsilon_{33}^{T}$ | Farad/m | $2.124 \times 10^{-8}$ |

For simulating damage, the two cubes were compressed under a quasi-static uniaxial load in the uniform compression testing machine at a loading rate of 0.3 MPa/s as shown in Figure 3. Three damage scenarios were introduced by manually controlling the applied load in the machine. The details for the damage stages are listed in Table 2. Next section presents the results of the experiments in detail.

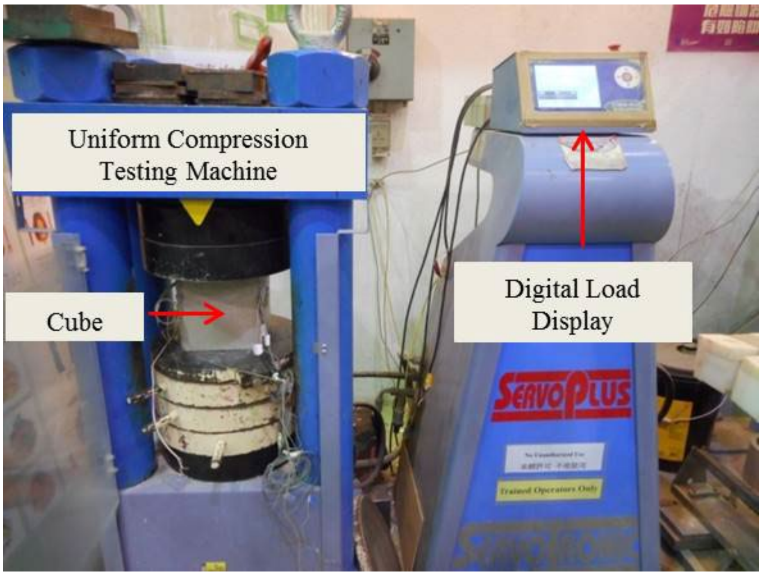



**Figure 3**: Controlled compression testing of cube specimen.

**Table 2**: Damage stages for the cubes.

| Stages | Nominal Stress (MPa) | |
|---|---|---|
| | Cube 1 | Cube 2 |
| Stage 0 | Undamaged (Day 28 after casting) | Undamaged (Day 28 after casting) |
| Stage 1 | 15.2 | 11.4 |
| Stage 2 | 22.2 | 26.8 |
| Stage 3 | 41.8 (Collapse) | 38.6 (Collapse) |

## EXPERIMENT RESULTS

### 1. Undamaged state (Baseline comparison)

The conductance signature of the two cubes was derived after performing data processing on the acquired time domain data in the low-cost EMI technique. The input signal was manually controlled and the raw initial data was in time domain (refer to Eqn (4)). The repeatability of the three piezo configurations was checked to establish their reliability respectively using a non-dimensional index called root mean square deviation (RMSD), which is given by the following equation:

$$RMSD(\%) = \sqrt{\frac{\sum\left(G_k^{r1} - G_K^{r2}\right)^2}{\sum\left(G_k^{r1}\right)^2}} \times 100 \quad (5)$$

where $G_k^{r1}$ and $G_k^{r2}$ denote the conductance reading for the $k^{\text{th}}$ frequency corresponding to set 1 and set 2, respectively. The maximum RMSD value found was 0.4% and 2.1% for the conventional and the proposed low-cost EMI technique, respectively. Figure 4 shows two typical signatures (EPC for Cube 2) and the repeatability of the conductance can be seen to be excellent. A typical comparison between the signatures of the conventional LCR meter and the low-cost proposed setup is plotted in Figure 5. Though the conductance signatures for the conventional and low-cost EMI technique are different, their trends are similar. The almost constant gap between the two measurements is possibly due to the parasitic influence of the connecting wires. Since the EMI technique relies on the relative change in values for damage identification rather than the baseline itself, the behavior exhibited by the low-cost EMI technique is acceptable. It was also observed that the best match between the low-cost alternative technique and the conventional LCR meter was for EPC.

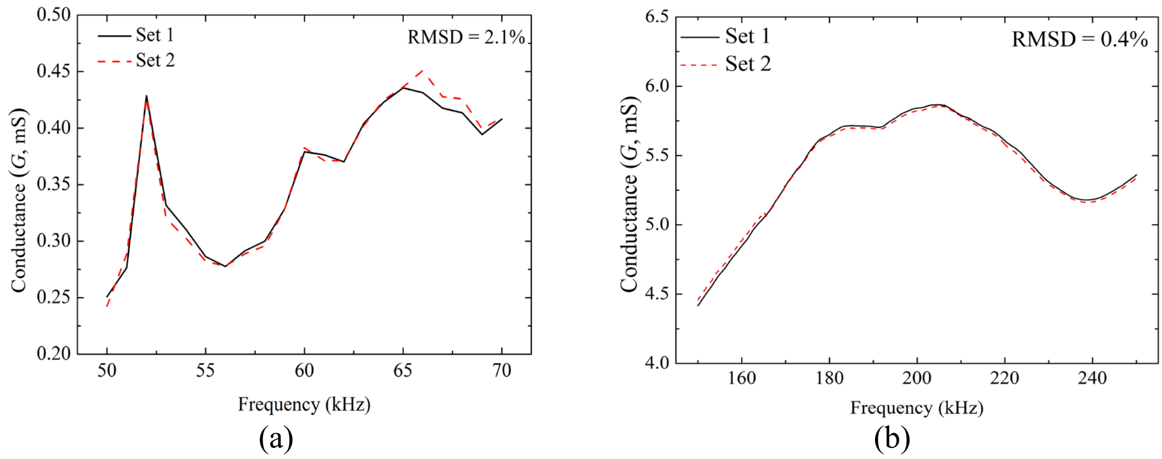



**Figure 4**: Repeatability of conductance signature for EPC in Cube 2 via (a) conventional EMI technique and (b) proposed low-cost EMI technique.

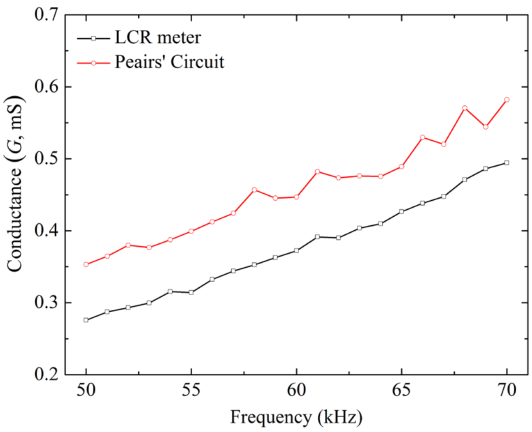



**Figure 5:** Comparison of conductance of proposed approach and LCR for EPC of Cube 2 on 19$^{th}$ day after casting (undamaged condition).

## 2. Damaged stages (Damage detection)

The damage severity assessment is usually realized via the RMSD value for the damage stage with respect to the undamaged one. A larger RMSD indicates a more predominant change in the signature and hence severer damage. The conductance signals for different damage stages obtained using the LCR meter and the NI Chassis for Cube 2 are shown in Figure 6. Only typical conductance information for Cube 2 is shown because the susceptance signals were found insensitive to the damage. The results for Cube 1 are not shown since trends are similar and also because the EPC got disintegrated after damage Stage 2. The figure shows that the signature trends for LCR meter and NI system are quite similar and consistent for each configuration. With the development of damage, the signatures experienced substantial changes, indicating that both techniques can detect the damage well. Comparison between different configurations shows that the SPC experienced the maximum change. In addition, the SPC and MWPC presented roughly similar signal trends. A striking observation is that despite being bonded far from the concrete cube, the MWPC was able to detect the damage successfully. This indicates that in practical applications, when direct surface attachment of PZT patches is not readily available, the MWPC can work as an excellent alternative choice.

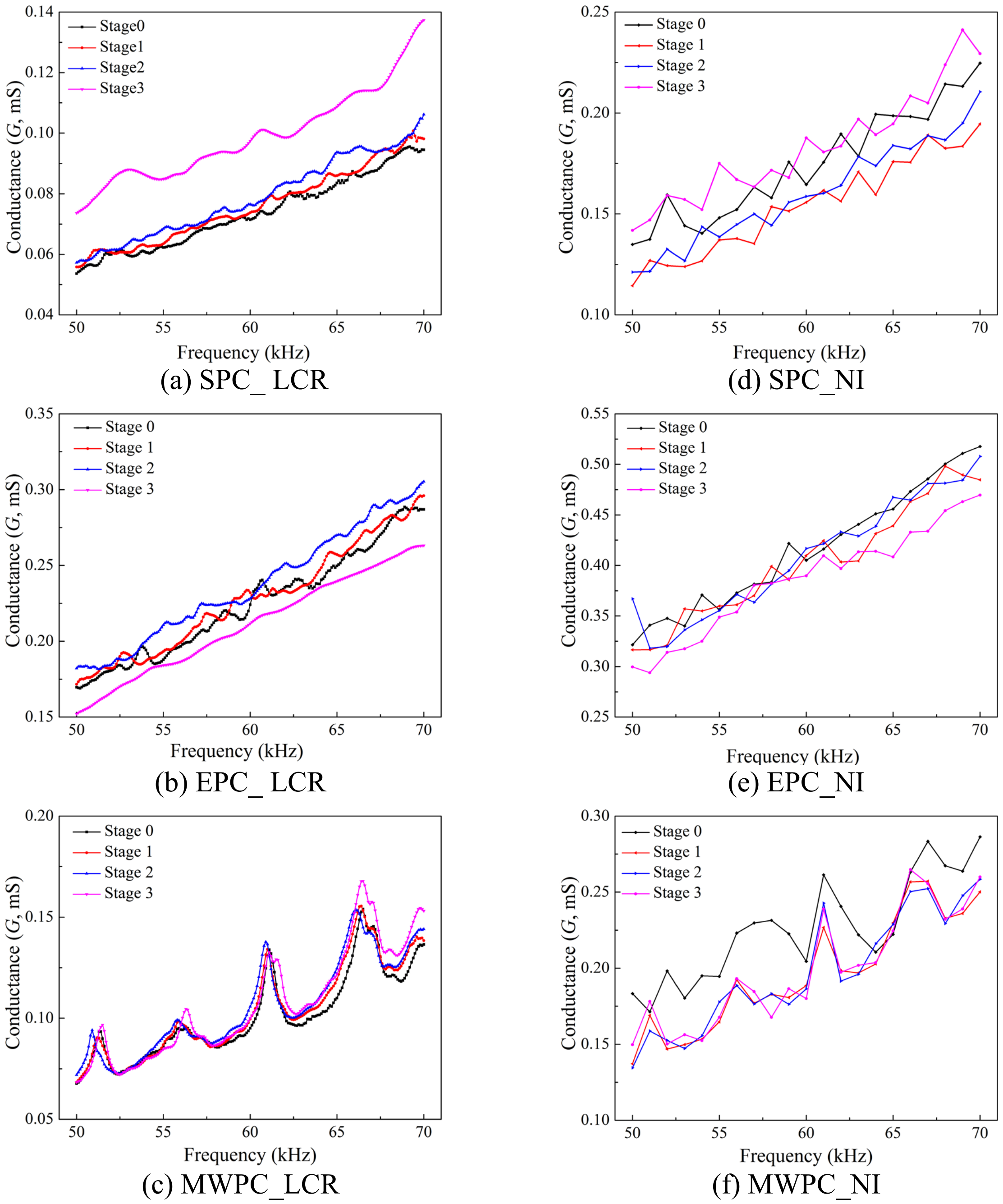
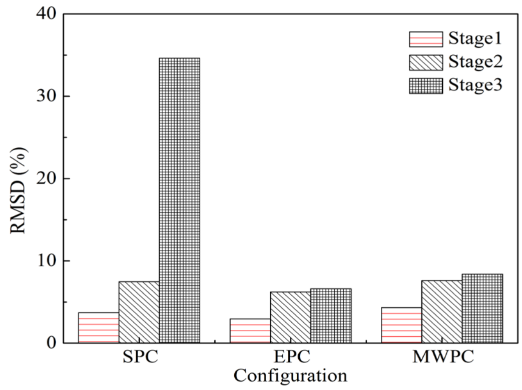
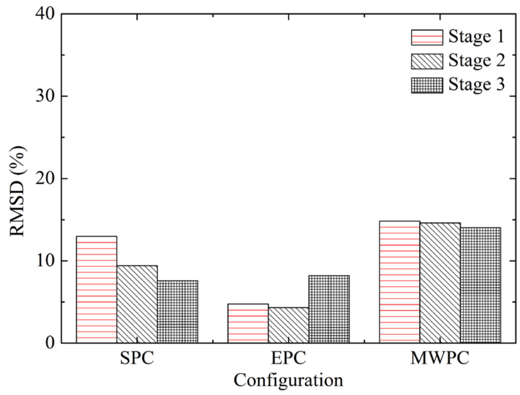



**Figure 6**: Comparison of conductance signature for different damaged stages using LCR meter and NI for SPC, EPC and MWPC in Cube 2.

For better comparison, the RMSD values are plotted in Figure 7. For the SPC, both the traditional and present low-cost techniques are able to detect the damage existence. However, the latter fails to differentiate different damage scenarios. For the EPC, the damage existence is effectively detected using both the techniques covering both existence as well as quantification. For the MWPC, the low-cost EMI technique presents better performance in terms of higher RMSD than the conventional technique for all three damage stages. However, it fails to define higher damage level efficiently as the conventional technique. Overall, the conventional LCR meter based technique presented satisfactory performance in detecting the presence and development of damage while the proposed low-cost EMI technique can only detect the presence of damage effectively. Hence, the low-cost EMI technique could be a boon for small scale laboratories for which LCR meter could be unaffordable.




(a)




(b)

**Figure 7**: RMSD based on conductance for SPC, EPC and MWPC in Cube 2 based on (a) conventional and (b) low-cost EMI technique for different stages of damage.

**CONCLUSIONS**

In this paper, a low-cost EMI alternative for acquiring the admittance signature has been proposed for the measurement of damage severity in concrete cubes for the first time for EPC and MWPC in addition to SPC. Admittance information was collected for the undamaged and different damage stages. The reliability of the proposed low-cost EMI technique was verified by checking its repeatability and comparing the results with the traditional EMI technique, which utilizes conventional LCR meter. The comparison was found satisfactory with similar trends of the conductance signature for all configurations with EPC exhibited most similar results. The SPC was found to be the most sensitive to the damage, and the MWPC and the SPC signals were quite similar. Hence, MWPC can be adopted as an excellent alternative in practice when the direct surface bonding is not feasible. The low-cost EMI technique was found to be reliable for detecting the presence of damage, but not the severity of damage.

Overall, this paper provides an effective trial that in practice the low-cost NI equipment can be applied to realize reliable damage detection for concrete structures. More experiments on concrete structures will be conducted in future. A more comprehensive study involving prototype structures has also been conducted and the results are being published elsewhere (Kaur *et al.*, 2016).

**ACKNOWLEDGEMENTS**

This work was jointed supported by The Hong Kong Polytechnic University (Project No. 1-ZVFH) and NSFC Joint Research Fund for Overseas and Hong Kong and Macao Scholars (Project No. 51629801). The second author is thankful to the Research Grants Council of the Hong Kong Special Administrative Region for the Hong Kosng PhD Fellowship Award.

**REFERENCES**

Bhalla S (2004) A mechanical impedance approach for structural identification, health monitoring and non-destructive evaluation using piezo-impedance transducers *Ph.D. Thesis*, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.

Bhalla, S, Kumar P, Gupta A and Datta TK (2009) Simplified impedance model for adhesively bonded piezo-impedance transducer. *Journal of Aerospace Engineering* 22(4): 373-382.

Bhalla, S, Gupta, A, Bansal, S, and Garg, T (2009) Ultra Low-cost Adaptations of Electro-mechanical Impedance Technique for Structural Health Monitoring. *Journal of Intelligent Materials Systems and Structures* 20: 991-999.

Giurgiutiu V, Zagrai AN and Bao JJ (2002) Embedded active sensors for in-situ structural health monitoring of thin-wall structures *Journal of Pressure Vessel Technology ASME* 124: 293-302.

Kaur N, Li LF, Bhalla S, Xia Y and Ni PH, (2016), Integration and evaluation of multiple piezo configurations for optimal health monitoring of RC structures, *Journal of Intelligent Material Systems and Structures* (Under review).

Kaur N and Bhalla S (2015) Combined energy harvesting and structural health monitoring potential of embedded piezo concrete vibration sensors *Journal of Energy Engineering* ASCE 141(4),D4014001:1-18

Kaur N, Bhalla S, Panigrahi R and Shanker R (2015) Evaluation of miniature impedance chip for structural health monitoring of prototype steel/ RC structures based on EMI technique. *Experimental Techniques*, accepted on Jan 20th, 2015 (in press), DOI:10.1111/ext.12146.

Liang C, Sun FP and Rogers CA (1994) Coupled electro-mechanical analysis of adaptive material systems: determination of the actuator power consumption and system energy transfer. *Journal of Intelligent Materials Systems and Structures* 5: 12-20.

Lim YY, Bhalla S and Soh CK (2006) Structural identification and damage diagnosis using self-sensing piezo-impedance transducers, *Smart Materials and Structures*, 15(3): 987-995.

Na S and Lee HK (2013) Steel wire electromechanical impedance method using a piezoelectric material for composite structures with complex surfaces, *Composite Structures* 98.

Naskar S and Bhalla S (2015) Metal-wire-based twin one-dimensional orthogonal array configuration of PZT patches for damage assessment of two-dimensional structures. *Journal of Intelligent Material Systems and Structures* DOI: 10.1177/1045389X15592480.

Ni YQ, Xia Y, Lin W, Chen, WH and Ko JM (2012) SHM Benchmark for High-rise Structures: A Reduced-order Finite Element Model and Field Measurement Data. *Smart Structures and Systems*, 10(4-5): 411-426.

Panigrahi R, Bhalla S and Gupta A (2010) A low-cost variant of electro-mechanical impedance (EMI) technique for structural health monitoring. *Experimental Techniques* 34(2): 25-29.

Peairs DM, Park G and Inman DJ (2004) Improving Accessibility of the Impedance-Based Structural Health Monitoring Method. *Journal of Intelligent Material Systems and Structures* 15: 129–139.

Song H, Lim HJ and Sohn H (2013) Electromechanical impedance measurement from large structures using a dual piezoelectric transducer, *Journal of Sound and Vibration* 332: 6580-6595.

Talakokula V, Bhalla S and Gupta A (2014) Corrosion Assessment of RC Structures Based on Equivalent Structural Parameters Using EMI Technique.*Journal of Intelligent Material Systems and Structures* 25(4): 484-500.

Talakokula V and Bhalla S (2014a) Reinforcement Corrosion Assessment Capability of Surface Bonded and Embedded Piezo Sensors for RC Structures. *Journal of Intelligent Material Systems and Structures*, 26(17): 2304-2313.

Xia Y, Chen B, Zhou XQ and Xu YL (2013) Field Monitoring and Numerical Analysis of Tsing Ma Suspension Bridge Temperature Behavior. *Structural Control and Health Monitoring*, 20(4): 560-575.

Xia Y, Xu YL, Wei ZL, Zhu HP and Zhou XQ (2011) Variation of Structural Vibration Characteristics versus Non-uniform Temperature Distribution. *Engineering Structures*, 33(1): 146-153.

Yang YW, Bhalla S, Wang C, Soh CK and Zhao J (2007) Monitoring of rocks using smart sensors. *Tunnelling and Underground Space Technology* 22: 206–221.