INTEGRATION AND EVALUATION OF MULTIPLE PIEZO CONFIGURATIONS FOR OPTIMAL HEALTH MONITORING OF RC STRUCTURES

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ABSTRACT

Since last two decades, the electro-mechanical impedance (EMI) technique has undergone extensive theoretical and experimental transformations coupled with the evolution of newer practical adaptations and variants. Notable among these are the metal wire based variant, the dual piezo configuration and the embedded configuration, over and above the conventional surface-bonded configuration. Though there is a plethora of EMI related research devoted to metallic structures, only a limited number of studies are available for reinforced concrete (RC) structures, which are characterised by more complex behaviour and pose multiple problems for the EMI sensors such as small range and high damping owing to heterogeneous constitution. The objective of this paper is to provide, for the first time, a comprehensive comparative study covering four different variants namely surface bonded single piezo configuration (SSPC), embedded single piezo configuration (ESPC), metal wire single piezo configuration (MWSPC) in EMI technique for SHM of a real life sized RC beam subjected to destructive testing. The paper also proposes a modified and more practical version of the dual piezo configuration called modified dual piezo configuration (MDPC), employing concrete vibration sensors (CVS). It is found that the MDPC is the most expedient among all variants in capturing the damage w.r.t. first occurrence of cracks and final warning of ultimate concrete failure. MWSPC is good in detecting the first level of damage, however its efficiency ceases thereafter when crack size increases. It can be considered as an alternative to SSPC in the scenarios when the damage level is low in concrete structures. The sensitivity of DPSC increases with increasing number of actuators connected in series due to increase in output current. In contrary to the SPC, the susceptance signature of MDPC is also sensitive to damage due to absence of capacitance part in its admittance signature (Song *et al*., 2014) and can be used for damage severity measurement for incipient damage level in concrete structures. The SSPC is found to be best in quantifying damage severity in terms of equivalent stiffness parameter and ESPC and MWSPC correlates well with the global dynamic stiffness of the structure. The low cost EMI technique was found to be reliable for ESPC and MWSPC for all stages of damage. However, it could not detect the damage stages after first level for SSPC. In overall, the proposed integration enables an early detection of damage, its propagation, and improved severity measurement for RC structures, thus contributing new application protocols.

Keywords: Metal wire, EMI, Dual Piezo, embedded piezo, CVS, RC structures, low cost EMI

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INTRODUCTION

Due to the development of newer reliable algorithms, miniaturization and cost reductions of digital computing hardware, structural health monitoring (SHM) is increasingly being implemented on real-life structures (Ni *et al.*, 2012; Xia *et al.*, 2013). There are two major categories of SHM, namely global dynamic techniques and local/ non-destructive evaluation (NDE) techniques. *Global techniques* essentially involve measurement of the modal structural response under low frequency excitations, of the order of 1-100 Hz. The main drawback of these techniques is that they rely on a relatively small number of low order modes, which, being global in character, are not very sensitive to the localized incipient damages (Bhalla and Soh, 2004a) and it many times gets contaminated by ambient vibrational noise and is affected by varying environmental temperature (Xia *et al.*, 2011). Contrary to the global techniques, the Local/ NDE techniques, namely ultrasonic wave propagation, acoustic emission, magnetic field methods, dye penetrant testing and X-ray radiography etc., rely on the localized interrogation of structures for detection and localization of structural damage. The main limitation of the above NDE techniques is that they may render the structure unavailable during the interrogation and work best when the possible damage location is known. The *Electro-mechanical impedance* (EMI) technique is an interface between the global dynamic techniques and the local NDE technique described above. The transducers used for the EMI technique are patches made of piezoelectric materials like Lead Zirconate Titatnate (PZT), and can act as both sensor and actuator simultaneously due to their direct and converse effect capabilities (Bhalla, 2004). In this technique, a PZT patch is subjected to an alternating voltage excitation from an impedance analyzer/ LCR meter, sweeping through a particular frequency range, generally a subset of 30–400 kHz and acquiring electro-mechanical admittance signature, consisting of the real (conductance, G) and the imaginary (susceptance, B) components. Hence, EMI technique has

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higher sensitivity (much more than the global techniques) to the incipient damage levels and not as cumbersome to implement on large structures as the local NDE techniques. Use of an array of piezoelectric transducers omits the requirement of damage location to be known a priori (Soh *et al*., 2000; Park *et al.*, 2001). Several other advantages of these transducers like low-cost, not effected by boundary conditions, fast dynamic response, long term durability and competitive performance, negligible ageing, immunity to noise, render them preferable for autonomous SHM. The different configurations of the piezo sensors used for the EMI technique in this paper are discussed in detail below:

Surface Single Piezo Configuration (SSPC) is used in the conventional EMI technique where, a single PZT patch is surface bonded on the host structure and it acts acts as sensor and actuator simultaneously. The governing one-dimensional wave equation for the generic system comprising one half of the patch and the structure was first solved by Liang *et al.* (1994) using the impedance approach. Using Liang's generic derivation, 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 $\left(\overline{Y_P}\right)$depending upon the parameters that depends on the properties of PZT patch alone and the properties of PZT patch and the structure

$$\overline{Y} = \overline{Y_P} + \overline{Y_A} = 2\omega j \frac{wl}{h}\left[\overline{\varepsilon_{33}^T} - d_{31}^2 \overline{Y^E}\right] + 2\omega j \frac{wl}{h}\left[\left(\frac{Z_a}{Z+Z_a}\right) d_{31}^2 \overline{Y^E}\left(\frac{\tan \kappa l}{\kappa l}\right)\right] \quad (1)$$

where, l is the half-length; w is the width and h is 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, ω the angular frequency and κ the wave number given by

$\kappa = \omega\sqrt{\rho / Y^E}$, here ρ 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 the above equation and hence, it serves as an indicator of the change in the state of health 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 is conventionally used for EMI technique for SHM of structures since last one and a half decade (Giurgiutiu *et al*., 2002; Lim *et al.*, 2006; Hey *et al.*, 2006; Yang *et al*., 2008; Bhalla *et al.*, 2009). More accurate models of piezo-bond-structure interaction have also come up in the recent years (Bhalla and Moharana, 2012; Moharana and Bhalla, 2014). Shanker *et al*. (2010) proposed the simultaneous application of the EMI and the global dynamic techniques using the same set of PZT sensor patches for SHM. Anamdas and Yang (2012) reported a practical investigative case study involving monitoring of excavation support structures using piezo sensors. Recently, a number of developments have been reported in the literature concerning the electronics aspects of the EMI technique (Overly *et al*., 2008; Hoja and Lentka, 2009; Margo *et al*., 2013).

Embedded Single Piezo Configuration (ESPC) is based on the use of Concrete Vibration Sensor (CVS) embedded in the host structure as shown in Figure 2. SSPC being fragile and exposed to the hostile environment can get tampered during the operational use of the host structure e.g. bridges etc. Hence, embedded CVS, which is a ready to use packaged sensor (CEL, 2016) is used for the 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 and Bhalla (2014, 2015) have rigorously used ESPC for monitoring corrosion in the concrete structures via EMI technique. Kaur and Bhalla (2014, 2015) used ESPC for monitoring damage in the RC structures. Comparison of ESPC with other piezo configuration is the novel aspect of this paper.

Metal Wire Single Piezo Configuration (MWSPC) is based on the use of a PZT patch surface bonded on one end of a thin aluminium wire as shown in Figure 2 and the other end of the metal wire is attached to the host structure. Despite of several advantages of SSPC, its fragile nature renders it unsuitable for the host structures with complex geometry and curved surface. Other practical concern with SSPC is supressed peaks in the case of concrete structures due to large damping. This results in lack of quick inferences, which can otherwise be drawn from the prominent change in peak frequencies and their magnitude in the conductance signature in concrete structures. To address the aforementioned issues, Na and Lee (2013) proposed MWSPC where the PZT patch is bonded on a metal (aluminium, here) wire rather which in turn is attached to the structure. Though the sensitivity of this configuration gets lowered, yet it proves to be a better alternative for the host structures with complex geometries where employing traditional SSPC becomes cumbersome. Upon excitation in MWSPC a stationary wave generated by the PZT patch travels to the structure via metal wire. Any change in the structural parameters due to damage effects the reflected wave thus altering the admittance signature which allows the damage detection (Naskar and Bhalla, 2014).

Modified Dual Piezo Configuration (MDPC) is derived from the dual piezo configuration (DPC) proposed by Song *et al*. (2014). In SPC, the impedance is measured by applying an input voltage to a single PZT and measuring the resulting current output from the same PZT.

Despite of having high sensitivity to locate the incipient damage level, damage detection for large civil structure like bridges etc. using SPC is found less effective. To address these issues, Song *et al*. (2014) proposed DPC in which a circular eccentric PZT consisting of two isolated but concentric PZT segments allowing independent excitation and sensing is used. The admittance for the piezoelectric transducers of same thickness in DPC is given by (Song *et. al*., 2014)

$$\bar{Y} = 2\omega j \frac{wl}{h}\left[d_{31}^2 \overline{Y^E} \left(\frac{Z_a}{Z + Z_a + Z_b} \right) \right] \tag{2}$$

where, Z_a and Z_b denote the mechanical impedance of the actuator PZT and sensor PZT, respectively. However, lack of commercial availability of concentric PZT patches, limits the practical application of DPC. Hence, Adhikari (2015) proposed to modify DPC by replacing the concentric PZT patches with commercially available square PZT patches. The researcher performed the SHM of a small aluminium block ($42 \times 42 \times 10$ mm^3) via MDPC employing a surface bonded single PZT patch for sensing and four PZT patches (connected in parallel) for actuation. This paper extends the application of MDPC to a more practical scenario considering a real life sized simply supported RC beam with set of five embedded CVS (shown in Figure 2) each encapsulating a square PZT patch. Also, the sensitivity of MDPC for EMI technique is investigated by varying the number of actuators.

Though there is a plethora of EMI related research devoted to metallic structures, only a limited number of studies are available for RC structures, which are characterised by more complex behaviour and pose multiple problems for the EMI sensors such as small range and high damping owing to heterogeneous constitution. The objective of this paper is to provide, for the first time, a comprehensive comparative study covering four different variants namely SSPC, ESPC, MWSPC and MDPC in EMI technique for SHM of a real life sized RC beam subjected to destructive testing. A low cost alternative for SHM of concrete structures with SSPC, ESPC, MWSPC has also been provided and successfully validated with the conventional EMI technique using expensive impedance analyser. The paper also proposes a modified (MDPC) and more practical version of the DPC, employing concrete vibration sensors (CVS). Also, the sensitivity of MDPC with varying the number of actuators for EMI technique is investigated.

EXPERIMENTATION DETAILS

After achieving encouraging results from the two cubes (size 150×150×150 mm^3, grade M30) with four different piezo configurations namely, SSPC, ESPC, MWSPC and MDPC, the authors were encouraged to proceed with a reinforced concrete (RC) beam. A set of experiments were carried out in the laboratory to compare different types of piezo configurations introduced above for SHM of a RC beam. The complete experimental set-up is shown in Figure 1. It consisted of a simply supported real life sized RC beam of span 4 m. The properties of the RC beam are given in Table 1. Concentrated cyclic load at varying frequency was applied on the beam by a hydraulic jack at two points 28 cm apart as shown in Figure 2. Typical load-displacement plot during one of the damage stage (Stage 2) is also shown in the Figure 2. Commercial raw PZT patches and CVSs, both procured from CEL (2016), have been used in this experiment. The properties of the PZT patch are given in Table 2. The complete instrumentation detail is shown in Figure 3. Assuming the beam to behave symmetrically under concentrated load, different piezo configurations were instrumented in one half of the RC beam at 'Mid', 'Offset_1' and 'Offset_2' location. Three PZT patches were directly bonded on the bottom surface of the beam with two part araldite epoxy adhesive and three PZTs were attached via metal wire (Figure 3). For the metal wires, the PZT patches were attached at its one end while the other end of the metal wire was bonded on the bottom surface of the beam. Three metal wires each having PZT patch at their end were attached at three locations namely 'Mid', 'Offset_1' and 'Offset_2' as shown Figure 3. Three sets of CVSs were embedded inside the RC beam flushing with its bottom at 'Mid', 'Offset_1' and 'Offset_2' (Figure 3). Each set consisted of one CVS at the centre acting as sensor (hence, denoted as 'S') and four CVS surrounding the later acting as actuators (denoted as 'A'). The admittance signature of the PZT patches was obtained using conventional LCR meter, model E4980AL (Keysight Technologies, 2016) for the SPC and MDPC. Two point and four point connections (Keysight Technologies, 2016) of LCR meter were used for SPC and MDPC, respectively. The time domain data for the surface bonded PZTs under impact load test was measured using 32-Channel Universal Recorder, model EDX 100A (Kyowa, 2016) with a sampling frequency of 5 kHz. The undamaged stage (Stage 0) for both RC beam and cube has been taken as the Day 28 of their casting. The intermediate stages of load designed to reach the ultimate failure of concrete in the RC beam and cube under concentrated cyclic load are listed in Table 3.

OBSERVATIONS AND RESULTS

In the first place, the repeatability for conductance signature of the four configurations namely, SSPC, ESPC, MWSPC and MDPC was checked and shown in Figure 4. For this section, MDPC consists of one sensor (S) and one actuator (A) (refer Figure 3) only. The conductance signatures presented in Figure 4 represent the undamaged condition. For SSPC, ESPC and MWSPC the conductance signature was acquired for frequency range of 150 kHz to 250 kHz. The conductance signature of MDPC was becoming negative after 140 kHz. Hence, the frequency range was chosen to be 50 kHz to 130 Hz for MDPC. All the four configurations have shown a very good repeatability with RMSD less than 1% which highlights the reliability of the data. The cracks which appeared on the RC beam under the concentrated two-point cyclic loading (Figure 2) during different damage stages (Table 3) till ultimate failure of concrete are shown in Figure 5. The conductance signature of SSPC, ESPC, MWSPC, MDPC for different damage stages was acquired for three beam locations. The same is shown in Figure 6 for Offset_2 beam location. The conductance value of SSPC and MWSPC are of the same order at the beam Offset_2 location (least damaged, being the farthest point from the centre). Hence, MWSPC can be considered as an alternative to SSPC in the scenarios when the damage level is low in concrete structures. It is observed from the plot that ESPC exhibits the highest conductance as compared to other piezo configurations considered here due to the constrained boundary conditions experienced by it. MDPC has the lowest conductance values because of using two different CVSs each for sensor and actuator separately. To compare the damage detection ability of the four piezo configurations considered in this study, the root mean square deviation (RMSD) of the conductance signature was determined. The RMSD value was calculated for each damage stage using the following equation (Shanker, 2011)

$$RMSD(\%) = \sqrt{\frac{\sum\left(G_k^d - G_k^u\right)^2}{\sum\left(G_k^u\right)^2}} \times 100 \tag{3}$$

where, G_k^u denotes the undamaged conductance value and G_k^d the conductance value after damage for the k^{th} frequency. The RMSD values for SSPC, ESPC, MWSPC and MDPC at three beam locations namely Mid, Offset_1 and Offset_2 for different stages of damage are plotted in Figure 7. It is evident from the plot that the MDPC is best among all piezo configurations considered here w.r.t. determination of first crack (Stage 1) and also the warning for ultimate failure of the concrete in the final stage. The possible reason for slightly higher RMSD values for MDPC and ESPC at Offset_1 than Mid is the application of two point concentric load on the RC beam. One of the point loads lies in the middle of 'Mid' and 'Offset_1' location (Figures 2 and 3). This might have resulted in local compression of the beam section near ‘Offset_1’ location resulting in slightly higher RMSD values of MDPC and ESPC (both based on embedded CVSs) than ‘Mid’ location. All stages of damage are very well detected by MDPC at the three beam locations. By the virtue of concentrated two-point load application at the centre of the beam, maximum stress is developed at the bottom surface of the mid beam location. Hence, the SSPC indicates the occurrence of surface cracks at mid location prior to ESPC. MWSPC on the other hand is most sensitive to the first level of damage after which the change in the RMSD values is not much protuberant. At Offset_2, where the least damage occurred, the SSPC and MWSPC are exhibiting similar RMSD values. Hence, MWSPC can successfully replace SSPC for incipient damages in concrete structures.

Sensitivity of MDPC with Varying Number of Actuators

It has been already shown in the previous section that MDPC was most sensitive to the damage in the RC beam as compared to other piezo configurations. However, in the previous section, two CVSs (one sensor and one actuator) were considered for MDPC. In this section, the increase in sensitivity of MDPC with increasing number of actuators is explored. Four different cases were considered in which MDPC has (i) one actuator (S+A), (ii) two actuators (S+2As), (iii) three actuators (S+3As) and (iv) four actuators (S+4As). The different actuators were connected in parallel in order to enhance the output current. The admittance signature was acquired for the four cases in the frequency range of 50 kHz to 130 kHz at three beam locations for different damage conditions using LCR meter. In this section, Stage 1 has been considered as the baseline data due to non-availability of data on the Day 28 (which has been considered as undamaged case in previous section). After Day 28 of beam casting, other equipments were installed for the global SHM of the RC beam (not included in this paper). The experimental admittance signature was influenced by the electromagnetic interference in the power supply due to several other equipments and infected it with unexpected peaks. Those peaks were removed by data softening software measures and the processed signature is used in this section. The conductance and the susceptance signature of a typical case for MDPC patches with increasing number of actuators at 'Mid' beam location for damaged Stage 1 is shown in Figure 8. An evident increase in the conductance signature is observed in the figure, which points towards further increase in the sensitivity of MDPC. Here, another critical observation is made that in addition to conductance, even the susceptance signature is showing increase with increasing number of actuators. This is attributed to increase in PZT parameters [Eq. (1)] with increasing number of actuators in parallel. Figure 9 shows the conductance and susceptance signature for MDPC with increasing number of actuators at 'Mid' beam location for different stages of damage. Also, a typical admittance signature of SPC (here, SSPC) is shown in this figure. From the figure, it is evident that for all stages of damage both conductance and susceptance values are increasing in MDPC. Hence, a clear improvement in sensitivity with increasing number of actuators is indicated. It is interesting to note that in contrary to SPC, where only the conductance signature is sensitive towards damage, in MDPC the susceptance signature is also showing good damage sensitivity because of absence of capacitive part in the MDPC admittance signature (Song *et al*. 2014). There is no ambiguity in concluding that the suscpetance signature for SPC is almost insensitive towards damage due to high influence of PZT parameters on it. This has already been quoted in literature by many researchers (Bhalla, 2004, Soh *et al*. 2000). Figure 10 shows RMSD based on the conductance for MDPC with increasing number of actuators at three beam location for different stages of damage. The fourth actuator at Offset_1 and Offset_2 beam location got disintegrated hence omitted for consideration in the results. It is observed that MDPC is able to detect the damage very well for all number of actuators. It should be accentuated here that with addition of two actuators clear increase in sensitivity is observed, however very little or no increase has been observed with addition of third actuator. Figure 11 shows RMSD based on the susceptance for MDPC with increasing number of actuators at three beam location for different stages of damage. It is observed that at the 'Mid' location though susceptance is sensitive to damage however the RMSD values are not increasing with increasing damage levels. This is attributed to that fact that the damage level is highest at the 'Mid' location and hence concluded that the susceptance is ineffective in the scenerios where the damage level is high in the concrete structures. The same observation got strengthened at the 'Offset_1' location when the susceptance can correctly indicate the damage levels in initial damage stages (Stages 2 and 3) however fails in Stage 4 when the crack depth increases. At 'Offset_2', being the farthest location from the load application point, the damage level is least compared to 'Mid' and 'Offset_1' location. Hence, susceptance correctly indicated about all the damage stages for all actuator cases at 'Offset_2' location.

Damage Severity Measurement using Equivalent System Parameters for SPC

The equivalent system parameters based on the experimentally observed trend of the real and the imaginary components of the mechanical impedance, '*x*' and '*y*', respectively, were extracted from the admittance signature of PZT patch. This was done for the SPC only, since this technique is not valid for MDPC (Bhalla, 2004). The raw admittance signatures of the SSPC, ESPC and MWSPC at three beam locations for different stages was acquired for a frequency range suitable subset of 100 kHz to 250 kHz, at an excitation voltage of 1 V (RMS) using the LCR meter. A close examination of the impedance components extracted from the experimental admittance signature using the parameters given in Table 2 [as outlined in Bhalla (2004)] suggested that the system behaviour was similar to a *mass-damper-spring* (*m*-*c*-*k*) series combination for which (Hixon, 1988)

$$\boldsymbol{x} = \frac{\boldsymbol{c}^{-1}}{\boldsymbol{c}^{-2} + \left(\boldsymbol{\omega}/\boldsymbol{k} - 1/\boldsymbol{\omega m}\right)^2} \tag{4}$$

$$y = \frac{-\left(\omega/k - 1/\omega m\right)}{c^{-2} + \left(\omega/k - 1/\omega m\right)^2} \tag{5}$$

Modified approach different from that given by Yang *et al.* (2007) has been adopted for determining the equivalent parameters for better match with the experimental *x* and *y* signatures. Assume, $x = x_1 = x_{avg}$ throughout the considered frequency range. Additionally, when *y*=0 and frequency $\boldsymbol{\omega} = \boldsymbol{\omega_0}$, using Eq. (4) it can be derived that

$$\boldsymbol{k} = \boldsymbol{m\omega_0^2} \tag{6}$$

Consider any frequency point $(\omega = \omega_1)$ with in the considered frequency range for which $x = x_1$ and $y = y_1$. Using the Eqs. (4) and (5) it can be derived that

$$c = \frac{x_1^2 + y_1^2}{x_1} \tag{7}$$

Further, using Eqs. (4), (6) and (7), following expression for mass '*m*' can be derived

$$m = \pm \frac{\left(x_1^2 + y_1^2\right)\left(\omega_1^2 - \omega_0^2\right)}{y_1\,\omega_0^2\,\omega_1} \tag{8}$$

The sign of '*m*' depends on the frequency point $(\omega = \omega_1)$ considered above. Here, *m* is considered positive when $\omega_1 < \omega_0$ and negative when $\omega_1 > \omega_0$. Using Eqs. (6)–(8), system parameters were derived at each measurement point within the frequency range and average values were obtained. For a typical case of ESPC at 'Offset_2' beam location, the average parameters were found to be *c* = 21.2493 Ns/m, *k* = 2.4733×10^7 N/m and *m* =9.668×10^4 kg. Figure 12 shows the comparison between the typical experimental plots of '*x*' and '*y*' and those of the equivalent system based on average values of the parameters *k*, *c* and *m* computed earlier. Reasonable agreement can be observed from the figure. The parameters were similarly worked out for SSPC, ESPC and MWSPC for different damaged stages of the RC beam and normalized stiffness at one typical beam location is shown in Figure 13.

The actual global static stiffness of the beam was calculated based on the slope of the static displacement (measured by LVDT at the 'Mid' beam location) and force (generated by the hydraulic jack) plot for different stages of damage (Figure 2). Table 4 lists the absolute global static stiffness for Stage 2 to Stage 4. Since, this method is based on the load application which started during Stage 1. Hence, static stiffness for Stage 0 does not exist and static stiffness for Stage 1is not given due to non-availability of data. The natural frequency of the beam was determined using the impact hammer test (Kaur and Bhalla, 2015) by hitting the beam with modal sledge hammer, model 8210, 12 lb. head (Bruel and Kjaer, 2016). The theoretical first natural frequency (f) for the undamaged condition (Stage 0) was calculated by substituting the RC beam properties (refer Table 1) in $f = \frac{\pi}{2L^2}\sqrt{\frac{EI}{\rho Db}}$ and using clear span of 3.85 m. It was found to be 20.24 Hz which is in good agreement with the experimental value of 20.9 Hz. The absolute global dynamic stiffness based on the first natural frequency for Stage 0 to Stage 3 is given in Table 4. The global dynamic stiffness for Stage 4 is not provided here because the impact hammer test was not performed on the RC beam due to the failure of concrete in Stage 4. The normalized values of global static (w.r.t. Stage 2) and dynamic (w.r.t. Stage 1) stiffness for different damaged stages are shown in Figure 14. Comparing Figures 13 and 14, it is observed that the equivalent stiffness for ESPC and MWSPC correlates well with the dynamic stiffness of the RC beam. Since the cracks appeared first on the surface hence the SSPC is found to be best in quantifying damage severity in terms of equivalent stiffness parameter. From the variation of global static stiffness it is also concluded that for lower incipient damage levels (Stage 1 to Stage 3) stiffness based on EMI technique is a good indicator of damage however for higher level of damage global static stiffness is very sensitive.

Low Cost Alternative for Damage Severity Measurement SPC

A low cost alternative for EMI technique which traditionally uses a conventional impedance analyser/ LCR meter typically costing USD 20,000 to 40,000 was proposed by Peairs *et al.* (2004). It is important to mention here that this technique cannot achieve the same level of measurement accuracy and repeatability as the SPC. Because the later employs conventional impedance analyzer which has sophisticated noise reduction and/or signal pre-amplifying schemes (Song *et. al.*, 2014). This low cost alternative has already been used for SSPC for lab size aluminium specimen in literature (Panigrahi *et al.*, 2010). However, this study explores its suitability for measurement of admittance for ESPC and MWSPC in addition to SSPC for real life sized concrete structures. In this technique, Peairs *et al.* (2004) proposed to use a FFT analyzer (typical cost USD 8000) in place of the impedance analyzer. Figure 1 shows the circuit proposed by Peairs and co-workers for admittance measurement. It consisted of a small resistance, connected in series with the PZT patch (bonded to the structure to be monitored). Upon applying an input sinusoidal voltage $\bar{V}_i$ across the combination through the FFT analyzer, the electric current $\bar{I}$ through the circuit is given by

$$\bar{I} = \frac{\bar{V}_0}{R} \tag{9}$$

where $\bar{V}_0$ is the output voltage across the sensing resistor R, fed into the measurement channel of the FFT analyzer. The PZT patch having infinitely large electrical impedance as compared to that of the resistor R, the coupled electromechanical admittance Y of the bonded patch can be expressed as

$$\overline{Y} \approx \frac{\overline{I}}{\overline{V_i}} = \frac{\overline{V_0}}{R\overline{V_i}} \tag{10}$$

Though the approach is very cost-effective yet it compromise on the damage sensitivity as compared to an impedance analyser as the later makes a truly stepwise measurement at each frequency of the prescribed range. The modified low cost technique considered here is based on the improved technique proposed by Panigrahi *et al.* (2010). This proposed technique provides improvement in sensitivity and is even more cost effective. A function generator is employed to generate the voltage signal $\overline{V_i}$ in place of 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 $\overline{V_0}$ at each excitation frequency and its phase lag with respect to $\overline{V_i}$ is measured (using NI Chasis Express) and hence, resulting in complex admittance function, much like the measurement of the impedance analyzer, using Eq. (3). The frequency of the imposed signal was incrementally varied with each measurement conducted under steady-state condition, much like the sweep mode available in impedance analyzers/LCR meters. As a result, this not only ensures higher measurement accuracy, but also eliminates bandwidth restrictions as encountered by Peairs and co-workers (2004) (Panigrahi *et al*., 2010). The total cost of the two pieces of equipment is about $5000 only.

Figure 1 shows the complete apparatus used for acquiring the admittance signature based on the Peair's circuit (Peairs *et al*., 2004) in a frequency range of 50-70 kHz. It consisted of the NI Chassis, model NI PXIe1071 (NI, 2016) with NI PXI 5105 Card and a function generator, model 33210A (Agilent Technologies, 2016). The frequency was changed manually in the function generator at a step interval of 1 Hz. Figure 15(a) shows the good repeatability of the conductance for ESPC in Cube 2 using Peair's Circuit with RMSD value of 2%. The comparison of the Peair's circuit and the conventional LCR conductance signature was done for SSPC, ESPC and MWSPC at three beam locations and two cubes on Day 19 of casting (*undamaged condition*) and the RMSD values are given in Table 5. One typical plot for the comparison is shown in Figure 15(b). From the Table 5, it is observed that this low cost alternative technique is most reliable for the ESPC with least RMSD values as compared to SSPC and MWSPC for concrete structures. Also, the RMSD values are very similar for the SSPC and MWSPC which indicate that MWSPC can be used as a representative of SSPC in undamaged stage of concrete structures. The damage severity measurement was done for the two cubes at the initial stage using this low cost EMI alternative to establish its reliability. The conductance signature of the two cubes was derived after performing data processing on the acquired time domain data. The comparison of conductance signature for SSPC, ESPC and MWSPC in Cube 2 acquired using the conventional LCR meter and Peair's Circuit is shown in Figure 16 for different damage stages. For better comparison, the RMSD plots are shown in Figure 17. For SSPC, the first level of damage was captured effectively; however, the low cost EMI technique is not able to correctly define the further damage stages. For ESPC, the damage severity was effectively measured using both the techniques, though conventional LCR again performing better. The performance of both techniques is comparable for the case of MWSPC, with low cost EMI technique performing better. The first level of damage was efficiently captured by both techniques for MWSPC. However, MWSPC is not able to define higher damage level in further stages efficiently by both the techniques. Similar behaviour was already proved for MWSPC in one of the previous cases (Figure 7). As the results were not very convincing for the concrete cubes and the technique is cumbersome in terms of data acquisition, hence, the studies were not continued further on the RC beam.

CONCLUSIONS

For the first time, a comprehensive laboratory based experimental study has been presented in this paper to compare various piezo configurations including SSPC, ESPC, MWSPC and DSPC for real life sized concrete reinforced structure. Admittance signature for different damaged stages before the ultimate failure of concrete was acquired for four piezo configurations placed at three locations in one half of the RC beam with span of 4 m. MDPC comes out to be the best among all other piezo configurations for detection of first crack and also for warning of ultimate failure of concrete. SSPC is better than ESPC as the cracks starts from the surface where the stress is maximum. MWSPC is good at detecting the first level of damage, however its efficiency ceases thereafter when crack size increases. It can be considered as an alternative to SSPC in the scenarios when the damage level is low in concrete structures. The sensitivity of DPSC increases with increasing number of actuators connected in parallel due to increase in output current. In contrary to the SPC, the susceptance signature of MDPC is also sensitive to damage due to absence of capacitance part in its admittance signature and can be used for damage severity measurement for incipient damage level in concrete structures. The SSPC is found to be best in quantifying damage severity in terms of equivalent stiffness parameter and ESPC and MWSPC correlates well with the global dynamic stiffness of the structure. A low cost EMI alternative for acquiring the admittance signature which was already used for SHM of aluminium structures has been used for the measurement of damage severity in concrete cubes for the first time for ESPC and MWSPC in addition to SSPC. The results are compared with the traditional EMI technique where conventional LCR meter is used. The low cost EMI technique was found to be reliable for ESPC and MWSPC for all stages of damage. However, it could not detect the damage stages after first level for SSPC. Hence, it was not continued further for the RC beam. Overall, this paper provides a clear outcome that MDPC is most preeminent for the SHM of large RC structures as compared to other configurations considered here. Hence, the proposed integration enables an early detection of damage, its propagation, and improved severity measurement for RC structures, thus contributing new application protocols.

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