Volume 9, Issue 5
October 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

A Review of Electromechanical Impedance Technique using Piezoelectric Transducers in the Assessment of Structures

[1]Harkirat Kaur and [2]Sarita Singla

[1]Department of Civil Engineering, Punjab Engineering College, Chandigarh-160012, India

[2]Department of Civil Engineering, Punjab Engineering College, Chandigarh-160012, India

E-mail: [1]harkiratkaur.phdciv@pec.edu.in, [2]saritasingla@pec.ac.in

ABSTRACT

Monitoring of a structure after its construction is as crucial as it is during its designing or construction. Properly monitored structure could avoid a lot of catastrophic accidents. Structural Health Monitoring (SHM) plays a vital role. Earlier analysis of the systems by professional experts was performed visually. Various Non-Destructive Tests (NDT) like Rebound Hammer, Ultrasonic Pulse Velocity Test, etc. are utilized for the inspection. Along with these piezoelectric transducers have proven to be another way if evaluation of the structures. Electromechanical Impedance (EMI) technique by means of piezoelectric materials has been widely carried out for the structural response at various stages. EMI has the potential to detect damages, corrosion and even the strength of any structural member. This review paper includes the various studies that evolved from the past decade related to EMI dealing with new concepts and ideas.

Keywords: *Structural health monitoring, smart piezoelectric materials, electromechanical impedance technique, finite element simulation.*

1. INTRODUCTION

SHM comprises scrutinization of response of any structure subjected to the present loading considering the environment conditions. It assesses the irregularity, deterioration that may affect safety or serviceability of any structural element [1]. Monitoring in continuation, procurement of the response, analysis of the test data to facilitate decisions are key aspects of SHM [2]. Recognizing the local or incipient damage in the early stages lead to the prevention of severe damage. The damage severity ranges from local damage to severe damage. Medium to severe damages may be easily visible and this type of damage changes the vibration response of the structure to a significant extent. The variation in the vibrational response i.e. shift in mode shapes, modal frequencies are identified through global techniques.

Identification of local damage is difficult to detect with global techniques because the frequency change or mode shape change is not so significant for local damages. Thus, to detect the local damages, local techniques are more relied on. Techniques in the local category are ultrasonic pulse velocity techniques detecting the soundness of the structure, acoustic emission, Impact Echo testing etc. These are usually immense techniques and leads to extraction of some information, which are history of load applied and strain formation, giving not much information on the incipient or local damage [3].

Smart materials have established to be a new way for SHM and NDT. Smart materials have the tendency to detect changes. One smart material is piezoelectric material. The word 'piezo' is a Greek term which means pressure. In 1880 Pierre and Paul Jacques Curie discovered the piezoelectric effect. Lead Zirconate Titanate (PZT), is one type of piezoelectric material.

In EMI surface waves are generated through the vibrations or excitations of the PZT patches. These waves travel outward radially. The waves play detects any defects or damage which tend to hinder its course. The technique involves the use of PZT either bonded on the host structure or embedded in. The patch is excited using alternating electric field through an impedance analyzer or an LCR meter. The analyzer then measures the electro-mechanical response of the patch in form of admittance. The analyzer plots real and imaginary parts of the admittance against the frequency range and are known as signatures. Fig. 1 shows the mechanism of the EMI technique through an LCR meter. The pristine signatures are considered as the baseline indicator. The damage occurring in the structure changes the signatures and the damage is then detected.

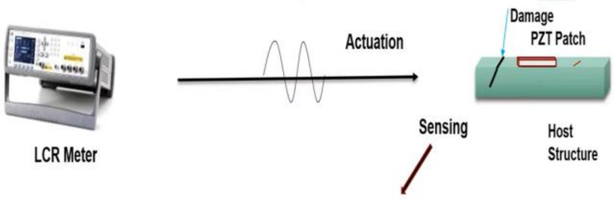

Fig. 1 EMI technique

In this article, the EMI technique and its various characteristics are focused. Various studies are mentioned that are conducted over the past few years in order to provide readers with a sight of how the technique has developed so far.

2. DEVELOPMENT IN THE EMI TECHNIQUE

Analytical theories of the relation between the bonded PZT's admittance signature and the structure's impedance are

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

derived by many researchers to date. A correlation between the electrical admittance ($\bar{Y}$) of the PZT patch and the host structure's impedance (Z) has been worked out. 1D analytical model was projected considering the excitations of the PZT patch in 1 direction under the applied alternating electric field E_3 in direction 3 [4]. Equation 1 shows the admittance signature for 1D model.

$$\bar{Y} = \frac{2\,\omega\, j\, w\, l}{h}\left[\left(\overline{\varepsilon_{33}^{T}} - d_{31}^{2}\overline{Y^{E}}\right) + \left(\frac{Z_a}{z+Z_a}\right) d_{31}^{2}\overline{Y^{E}}\,\frac{\tan kl}{kl}\right] \quad (1)$$

The limitation of the model was the consideration of the transfer of force at the ends of the patch only. The model could not be used for 2D and 3D structures. A 2D impedance approach was proposed incorporating direct impedances (Z_{xx} and Z_{yy}) and cross impedances (Z_{xy} and Z_{yx}) and these are associated with planar force F1 & F2 and its equivalent planar velocity $\dot{u}_1$ and $\dot{u}_2$ [5]. The system is highly indeterminate as it has four complex variables from two known equations of admittance's real and imaginary part to find. Another limitation of this 2D model was the assumption of the force transmission occurring at end points of the PZT patch only.

A simplified 2D impedance model was proposed that considered the effective displacement and effective impedance built on with the assumption that force from the PZT is spread through its the boundary [6]. Equation 2 displays the formulation of refined admittance signature for a 2D model. Here, $Z_{s,eff}$ stands for impedance of the host structure.

$$\bar{Y} = \frac{4\,\omega\, j\, l^{2}}{h}\left[\overline{\varepsilon_{33}^{T}} - \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\nu)} + \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\nu)}\left(\frac{Z_{a,eff}}{Z_{s,eff}+Z_{a,eff}}\right)\frac{\tan kl}{kl}\right] (2)$$

The 2D plane strain was further formulated by taking into consideration of extensional actuation along the length of the patch and longitudinal actuation along the patch thickness i.e. the 3D vibrations of the PZT [7]. Both the PZT patch and adhesive bonding layers are considered as integral parts of the 3D impedance model. The 3D model is valid for interaction with both embedded and surface-bonded PZT structures. All the previous analytical models considered the single PZT patch for monitoring. The mass of a patch is negligible and can be ignored. But in case of multi patches the mass of the PZTs cannot be neglected. A multiple PZT-structure model where N number of PZTs were considered for damage detection was analyzed and the masses of multiple PZT transducers were considered in the model [8].

3. EMI TECHNIQUE THROUGH SHEAR LAG EFFECT

In the EMI application, the structure is monitored with a PZT which is a smart material. The patch is bonded through an adhesive bond layer on the structure to be monitored. The bond layer acts as the layer of interfaces between the PZT and the structure. The real and imaginary admittance signatures depend on the mechanism of transmission of stress and strain from the PZT to structure through this bond layer. Various researchers have worked on incorporating the shear effect into the EMI technique.

The adhesive layer's contribution in the interaction of the PZT patch and host was taken into account in the model. The adhesive's finite thickness and elasticity property were considered in the mechanism of measuring the admittance signatures. The converse effect of the patch was taken into consideration i.e. was taken only as an actuator [9]. The interaction of the PZT and the structure was assumed to be 1D in nature by considering the effect in one axial direction only. The patch was assumed to be actuated in pure bending and with linear variations of strain along the thickness of the beam. The adhesive layer deformed in pure shear. From the results displayed, reduction was observed in the strain output from the patch because of the deformation in the adhesive layer. A shear lag ratio "ξ " was presented as

$$\xi = \left[\frac{\epsilon p}{\epsilon b} - 1\right] \quad (3)$$

where εp and εb represents strains in bonded patch and the adhesive layer respectively. The theoretical model showed that the PZT in its direct effect i.e. as a sensor appeared as if its dimensions were smaller than in actual. This is because of the shear lag effect. The transferring of strain between the patch and the structure was further analyzed based on the Euler–Bernoulli beam theory [10].

An expression for 'effective length', l_{eff}, of the PZT acting as a sensor was given [11], as

$$\frac{leff}{l} = 1 - \frac{\tanh(\Gamma l)}{\Gamma l} \quad (4)$$

$$\Gamma^{2} = \left(\frac{Gs}{Ep\ t\ ts} + \frac{3\ Gs\ wp}{Eb\ tb\ t\ wb}\right) \quad (5)$$

Gs is the bond layer's shear modulus, E_b is the Modulus of elasticity of beam, t_s and t are the thickness of the adhesive and PZT respectively and w_b the width of the beam. It was determined that for Γ > 30 cm-1, the shear lag effect can be expected as insignificant and can be assumed that the force is transmitted efficiently across the ends of the patch to structure. The drawback of this above approach in EMI application was that it is incomplete because in EMI technique, the PZT's both action that of the sensor and actuator effects are employed simultaneously.

A damper-mass-spring system was considered in order to treat the host structure which is to be monitored, the PZT patch and the adhesive used to bond the PZT to the structure all three together [12]. Liang 's model has been altered with the incorporation of the bonding layer's mechanical impedance (Z_b). Fig. 2 shows the impedance of the bond layer placed 'in series' with the structural impedance (Zs) of the structure can be expressed as a combination of impedances in series.

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

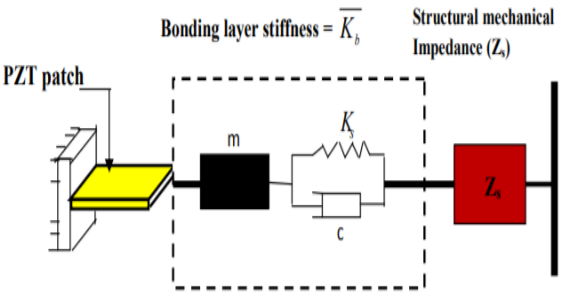

Fig. 2 Damper-mass-spring combination

An effective parameter was suggested to be incorporated in the sensor's evaluation. This parameter was based on the length of the PZT. This was done to study the shear lag effect. But this approach only considered the parameter for the senor and not for the actuator [13].

In order to incorporate the shear lag effect in analytical solution of the admittance signatures of the patch, a thorough derivation was suggested, assuming the shear deformation of the bond layer is pure [14]. This research which was based on various parameters, determined if adhesive of higher modulus of rigidity along with smaller thickness is applied to bond the patch to the structure then it confirms improved and better transmission of strain from structure to patch and vice versa.

The effect of the type of the bond layer and its variation in thickness both were experimentally studied [15]. It was observed that both the adhesive configuration and the thickness through the adhesive bond layer could significantly affect the measured EMI signatures from the PZT patch.

Many researchers also studied the dynamic conduct of a piezoelectric sensor [16]. A combined system's simulation model based on the 2D electro-mechanical behavior was carried out by both numerical simulation and analytical proportional study. It was concluded that the loading frequency should not be too high so as to ensure accuracy in the output obtained from the sensor. It was also concluded that the material combination of the sensor and the host structure needs to be cautiously chosen in order to progress in the sensor's efficiency.

A circular PZT patch was experimentally studied and was found out that the frequency effected the adhesive bond layer to an extent [17]. It was also concluded that the losses of the adhesive layer due to shear deformation are prime near the first frequency of radial resonance. The model's limitation was that the model overlooked the inertial parameter of the adhesive bond layer and also was assumed that the piezoelectric sensor was active only along the edges of the host structure.

Significant effects were observed due to the consideration of the bond layer in the analysis. Because of the bond layer, the amplitude and phase angle of the measured electrical signals were altered. And also, there was observed alterations in terms of the measured EMI admission range [18]. It was detected that more capable of identifying the weakening of the adhesive layer was the imaginary part i.e. the susceptibility of electrical admission.

A numerical study-based modelling was carried out to comprehend the effect of the adhesive as the bond layer on the measured admittance signatures through the coupled electro-mechanical effects of the PZT patches bonded to the structure [19]. Strain and the displacement of the deformed bonded interface showed a non-linear trend. It was also stated that the potential established around the patch varies for different thickness of the adhesive bond layer, when the structure is subjected to a known force. Mechanical effects due to the thickness of the adhesive alters the strain and the electric effects alters the electric potential generated across the patch. They also conducted parametric study along the bond for stress and strain profile, and found that the length of the sensor affects the shear stress. Shear forces at the ends of the PZT sensor create a localized effect, where the shear stresses high. On the other hand, if the PZT sensors are small in length, the mechanism for transmitting forces throughout the interface is entirely via shear stress

Some accurate analytical solution was formed considering the shear lag phenomena analytically. Fig. 3 shows the shear lag phenomena. The earlier models overlooked the inertial effect of the PZT but here was taken into account to form shear lag model. The new model considered both the shear lag and inertia effects simultaneously. The predictions of the new model matched more accurately with the experiment [20].

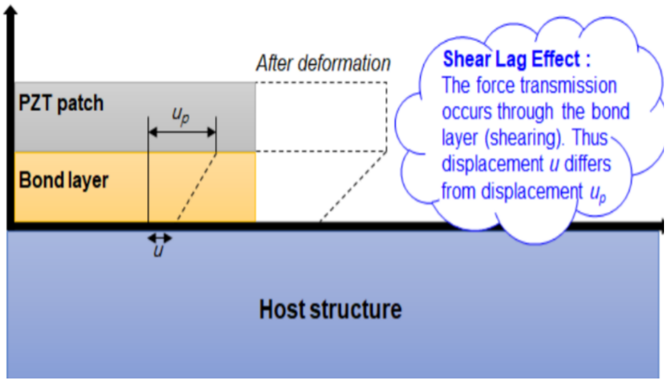

Fig.3. Shear Lag Phenomena

4. DAMAGE QUANTIFICATION METHODS

After the admittance signatures are obtained, statistical measures are incorporated to quantify the damage. Some of the measures are the root mean square deviation (RMSD) [21], relative deviation (RD) [22], mean absolute percentage deviation (MAPD) [23]

$$\text{RMSD}\ (\%) = \sqrt{\frac{\sum_{i=1}^{N}\left(G_i^1 - G_i^0\right)^2}{\sum_{i=1}^{N}\left(G_i^0\right)^2}} \qquad (6)$$

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

$$\text{RDi} = \frac{\sum_{k=1}^{N}(G_{ik}^{1}-G_{ik}^{0})^{2}}{\sum_{k=1}^{N}(G_{1k}^{1}-G_{1k}^{0})^{2}} \qquad (7)$$

$$\text{MAPD} = \frac{100}{N}\sum_{i=1}^{N}\frac{G_i^1-G_i^0}{G_i^0} \qquad (8)$$

G_i^1 : post damage conductance at the ith measurement point and G_i^0: corresponding pre damage value.
Of all the measures, RMSD is the one broadly used.

In case of multi-sensing scenarios where PZTs are connected in parallel and in sequence, dynamic metrics were suggested such as moving root mean square deviation, moving mean absolute percentage deviation and moving cross correlation [24].

Another damage quantification through EMI involves Impedance Based Identification (IBI) [25]. Impedance of the structure (Z) is complex in nature (Z = x + yj) and x, y are the function of stiffness, mass and damping. IBI involves solving inverse problems. From the plots of G and B ($\bar{Y} = G + Bi$), x and y are obtained. With the variation in x, y the dynamic parameters can be known.

5. PRACTICAL ASPECTS

5.1 Commercially available piezo material

PZT patch is available generally in circular or square size with the width varying from 5 mm to 80 mm and thickness 0.1 mm to 30 mm with both electrodes available on one side to easily do the soldering of wires to it [26]. Fig. 4 shows a PZT patch. In addition to these basic versions, the piezo industry manufactures piezo transducers based on the application. There are PZT-cement composite, ready to use wrapped sensor for RC structures [27]. They are treated as the smart aggregates and is often termed as Concrete vibration sensors (CVS). Kaur and Bhalla [28] used CVS in a concrete beam of length 4 m for its SHM and energy harvesting.

These PZTs are unable to bond properly with the curved surfaces. Thus, to overcome this another smart material is available known as Macro Fiber Composite (MFC) manufactured from unidirectional piezo active fibers enclosed by a polymer matrix, imparting a flexible texture [29]. Fig. 5 shows an MFC.

Fig.4. PZT patch

Fig.5. MFC

5.2 Selection of frequencies for the EMI technique

To study the assortment of frequency, a portion of concrete was studied using PZT in frequency ranging 30 kHz to 400 kHz. The intervals were separated into 6 groups (30–100 kHz, 100.1–150 kHz, 150.1–200 kHz, 200.1–250 kHz, 250.1–300 kHz, and 300.1–400 kHz) and each group was assessed under damaged state. The results showed that damage near the periphery of PZT significantly changed the impedance signatures around the high frequencies while damage far away from the sensor significantly altered admittance signatures in the lower frequencies [30].

Where there are no peaks in the frequency interval, any structural damage may not be detected by the EMI technique. The changes in the impedance signature, without any resonance occurring, might not be important. Therefore, a frequency spectrum of resonance must be established.

5.3 Hardware for the EMI technique

From the initial time period of the application of the EMI practice, it is being applied most commonly using an impedance analyzer such as Agilent 4194 A. Fig. 6 shows a Agilent 4194 A. This equipment is a high costly one. Thus, this motivated the use of the EMI technique at a lower cost, as an impedance analyzer can cost up to US$ 40,000 [31].

Fig. 6 Impedance analyzer by Agilent 4194 A

Various researchers tried to introduce a low-cost alternative for the application of the EMI technique using a Fast Fourier Transform (FFT) analyzer along with a simple circuit (voltage divider) [32]. Fig. 7 shows such a circuit. Under this approach, dividing the voltage (Vi) which is applied as the input with the

Volume 9, Issue 5
October 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

current passing through the sensor can be taken as the approximated value of the impedance (Z). Various researchers have been continuing to investigate the development of a low-cost EMI technique.

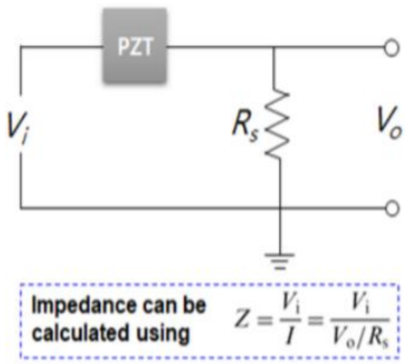

Fig.7. impedance measuring device

A functional generator named HP33120A with a two-channel DAQ card was also used for the measuring of the admittance signatures [33]. Further work on an integrated low-cost system can also be found [34-36]. The EMI technique is a method for detecting damage. That is very effective in evaluating the health of the surrounding area. This technique possess difficulty in case of the large-scale structure's monitoring because the large-scale structure requires a large in number up to thousands of piezo transducers. This many transducers will not only be expensive but also due to these wired sensors it would be difficult to manage them all together. To solve the issue related to wiring, now a days the importance of wireless sensor has increased. Various researchers have used AD5933 chip as the wireless systems that measures impedance [37]-[38]. This is manufactured by Analog Devices, Inc. The utility of Fast Fourier Transform (FFT) is associated with the chip itself. This acts as an analog to a digital converter and a digital to analog converter. Moreover, a small impedance measuring device was also commercialized by the company and named the chip as the 'AD5933 Evaluation Board' shown in Fig. 8. This chip measures impedance up to 150 kHz. Currently the chip containing board is sold for around US$ 100. It has been used in many applications of the EMI technique.

Table. 1 The various types of PZTs along with their properties

		Unit	PIC151	PIC255/ PIC252[1)]	PIC155	PIC153
Physical and dielectric properties						
Density	ρ	g/cm³	7.80	7.80	7.80	7.60
Curie temperature	T_c	°C	250	350	345	185
Relative permittivity — in the polarization direction	$\varepsilon_{33}^T/\varepsilon_0$		2400	1750	1450	4200
⊥ to polarity	$\varepsilon_{11}^T/\varepsilon_0$		1980	1650	1400	
Dielectric loss factor	$\tan\delta$	10^{-3}	20	20	20	30
Electromechanical properties						
Coupling factor	k_p		0.62	0.62	0.62	0.62
	k_t		0.53	0.47	0.48	
	k_{31}		0.38	0.35	0.35	
	k_{33}		0.69	0.69	0.69	
	k_{15}			0.66		
Piezoelectric charge coefficient	d_{31}		-210	-180	-165	
	d_{33}	10^{-12} C/N	500	400	360	600
	d_{15}			550		
Piezoelectric voltage coefficient	g_{31}		-11.5	-11.3	-12.9	
	g_{33}	10^{-3} Vm/N	22	25	27	16
Acousto-mechanical properties						
Frequency coefficients	N_p		1950	2000	1960	1960
	N_1		1500	1420	1500	
	N_3	Hz · m	1750		1780	
	N_t		1950	2000	1990	1960
Elastic compliance coefficient	S_{11}^E		15.0	16.1	15.6	
	S_{33}^E	10^{-12} m²/N	19.0	20.7	19.7	
Elastic stiffness coefficient	C_{33}^D	10^{10} N/m²	10.0		11.1	
Mechanical quality factor	Q_m		100	80	80	50
Temperature stability						
Temperature coefficient of ε^T_{33} (in the range -20 °C to +125 °C)	$TK\,\varepsilon_{33}$	10^{-3}/K	6	4	6	5

Volume 9, Issue 5
October 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Fig. 8 Impedance analyzer by Agilent 4194 A

The principle of EMI technique that incorporates both the direct effect (sensor) and converse effect (actuator) of the PZT patch simultaneously makes the increased amount of usage of PZTs. The ceramic PZTs are mostly in use for the EMI related research. Along with PZT ceramic, piezoelectric diaphragms (buzzers) were too proved as efficient in the application of the technique [39–41]. But because of the behavior of PZT transducers which are ceramic naturally, they are brittle in nature and this leads to its breakage whenever they are exposed to loading or environment. Some difficulty arises when they are to be attached to the curved surfaces for its monitoring. Many researchers [42]–[47] have therefore investigated the use of macro-fiber composite (MFC) formed by the NASA Langley Research Center [48]. They are formed with a number of adhesive layers. The approach leads to more flexibility along with durability of the transducers. And this makes MFC more suitable for mounting on curved surfaces such as pipes, domes, circular columns, etc.

6. SIMULATION

An insightful view of the Finite Element (FE) modelling approach was proposed [49] for the simulation of PZT structure interaction. Earlier application of FE modelling incorporated the use of low frequencies. The FE models were then applied to EMI techniques involving high frequencies [50]-[51] and showed good comparison with experiments. Bhalla [52] incorporated FEM for the effective impedance analysis in 2D. The real part of admittance for non-coupled and coupled field FE analysis was compared [53]. The latter has shown greater agreement with the findings of the experiment. Many researchers then have carried the coupled field analysis of the EMI technique on various specimens in ANSYS [54]-[61]. Another reliable software simulation is ABAQUS. Many researchers have carried out the simulation in ABAQUS [62]-[65]. If the simulations are appropriately performed then there could be a good agreement between the experiment and FEM results. Fig. 9 shows the comparison between simulation and experimental results.

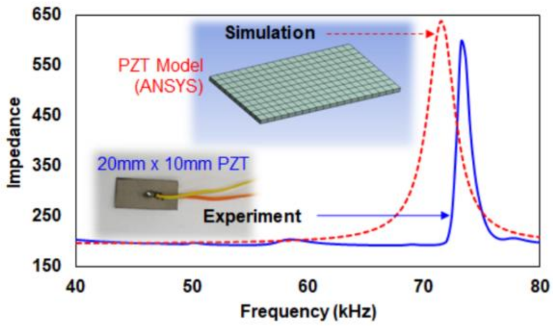

Fig. 9. Simulation v/s Experimental signatures

7. EMI TECHNIQUE WITH ARTIFICIAL INTELLIGENCE

Now the EMI technique is not only limited to electro-mechanical fields for a few days, but is also applied through the incorporation of machine learning. One of them is Artificial Neural Network (ANN) application with EMI practice. As the main objective of Structural Health Monitoring is to identify position and severity of the damage and the estimation of remaining life of the host structure. Many authors used the EMI technique to study how admittance signatures of the PZT alters after they are subjected to changed extents and positions of deterioration.

Several researchers asserted the utility and functionality of ANN along with the application of EMI technique for the monitoring. During the combination of ANN applied to the EMI technique then the procedure which usually is called an algorithm, requires a decent amount of training to identify the damage with success. Few communal forms of ANN techniques are shaped [66]. Here, the researchers used circular plates for the application of EMI along with ANN. The plates were based on aluminum alloy with a diameter of 100 mm and 1,6 mm thick. A featured extraction algorithm was applied with the probabilistic neural network (PNN) algorithm for the aforementioned study.

Compressive strength of concrete cubes was predicted using various predictive models [67]. ANN was combined with EMI technique to predict concrete strength through a 28-day monitoring of impedance signatures during concrete cure. Training of ANN algorithm was made using the test data. Various inputs were given for the training of the code which includes water/cement ratio, composition of concrete, compaction, curing, temperature, and CC values measured from admittance signatures of the PZT. With minimal error the strength of the concrete cube was estimated using the ANN model.

In conjunction with the EMI damage identification technique [68] a forward NN was applied. It was a multi-layer with a back-propagation algorithm. Many experiments were conducted in assessing the projected technique. A lab sized model of a pipe structure and a box

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

girder bridge was constructed. Both were exposed to loosen bolts and crack were introduced in the structure as damage. Using the developed PNN algorithm, Na and Lee [69] used 200 mm x 200 mm glass-epoxy composite plate and 4 PZT transducers were attached to each of the 4 corners of the plate to predict where damage was. Six various regions were differentiated for undergoing the test and 30 holes were drilled. Out of 30, 24 holes were properly forecast using ANN technology leading to 80 per cent of accuracy rate. The study stated that the accuracy rate could be improved by increasing the test data required for the training of ANN algorithm.

Palomino et al. [70] used the PNN and Fuzzy cluster analysis methods on an aluminum panel plate to classify damages of two different types. Different type of damages induced were cracks and the loss of rivets on a panel. The researchers stated the position of the PZT transducer to be very crucial in successful implementation of the damage identification. Predictive methods like PNN, simplified fuzzy network were applied to experiments based on an aluminum plate bonded with PZT transducers. The findings showed positive results in the identification of successful damage.

8. APPLICATION

Australian bridges are designed for a life span of 100 years. The Sydney Harbor Bridge is fitted with 2400 sensors to detect traffic damage, wind damage, temperature, vibration and severe events. Monitoring with sensors adds an extra level of safety. The Jindo Bridges are twin cable-stayed bridges with three continuous spans. Both bridges have existing SHM systems based two seismic accelerometers, 15 piezoelectric accelerometers, 15 thermometers, 15 strain gauges, 24 Fiber Bragg Grating sensors etc. The existing SHM system is quite versatile. The circle Line – MRT (Mass Rapid Transit) cluster in Singapore was constructed during 2005 – 2012. This linked all the radial MRT lines landing to the city. It is installed with 212 strain gauges, 64 temperature sensors, 21 sensors to detect deformation and 60 sensors of PZT. The SHM system controls the stability of the sheet piles which supports the soil during the deep excavation. These sensors were mounted on the struts that supported the sheet piles. The monitoring was done for the period of 1 year.

The EMI technique was used to determine the dental implant quality after surgical placement. The research was to degrade samples by using nitric acid and to correlate the amount of calcium loss with obtained impedance signatures [71]. Over the first 28 days, monitoring the hydration of cement materials was conducted [72].

The EMI technique was implemented to monitor the excavation of soil which was carried out so as to construct a road transport station. PZTs were mounted on a temporary support structure used to avoid collapsing of soil. The impedance signatures were obtained throughout a year. There was no damage. It was observed that the EMI technique was able to detect variations in load pattern caused by the soil surrounding the support [73].

Research also shows the application of EMI technique on PSC girder bridges [74]. The prestress forces loss occurring in the girders was examined based on the signatures as differences in peak and magnitude of signatures indicated different force stages.

The ability of EMI technique to track human and rabbit bone conditions was examined [75]. The research comprised the identification of cracks and fractures and the healing process succeeding a fracture. Furthermore, improvements in density of bone were too pursued based on the signatures.

The presence of crack or notch identification using EMI technique is one of the EMI technique's most researched zones [76]-[79]. Compared to the statistical measures discussed, a well-built correlation can be perceived between the distance and extent of the damage.

9. PRACTICAL ISSUES

Most of the practical was conducted under laboratory-controlled conditions. Although the impedance signature is altered due to damage, other factors corresponding to temperature fluctuations and PZT's durability can also cause the change in signature leading to false interpretation. The admittance signature of the patch kept inside and in outside environment for about 15 months were observed, and it was found that the safety of silicone rubber with which a patch was covered resulted in RMSD values below than the one which was not covered [80].

Another experiment was conducted where the temperature was varied. After the experiment the observed signatures showed the shift in the peaks and the magnitude was also varied indicating the softening of the stiffness of the host structure due to the variation in the temperature. The authors used correlations to reduce signature variability due to temperature shifts by moving the signature horizontally [81].

Park et al. [82] discovered that the real part of the impedance signatures should be favored to the imaginary part for taking into account the identification of damage, as they discovered that the real part changed only insignificantly with variations in temperature.

10. DAMAGE INDENTFICATION IN BONES

Human skeleton exhibiting bones is an excellent natural framework. The bones also exhibit structural properties i.e. mass, stiffness, damping, Modulus of Elasticity, poison's ratio etc. This framework is suitable for the detection of its damage through the EMI technique using smart materials i.e. the PZTs bonded to the bones for the detection/identification of damage. PZT transducers

Volume 9, Issue 5
October 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

were bonded to the bones to determine its dynamic properties [83]. Dynamic parameters like modal frequencies and damping ratios were derived from FRF. Fig. 10 shows the experimental setup of the determination of dynamic properties of the bone.

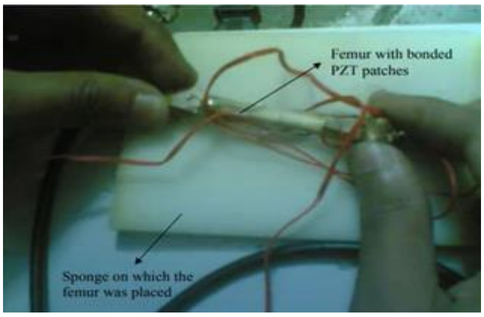

Fig. 10 shows the experimental setup of the determination of dynamic properties of the bone.

FE modelling in PZFlex software was carried out to study the effect of direct and converse effect of the piezo using coupled field analysis. The modeling was investigated for bone's phycological damage [84]

11. FUTURE WORK

The application of EMI technique using drones is at the very early stage of research. While the drone surveillance technology focused on visual inspection is progressing, this application with the drones is unable to detect internal damages as it is difficult to detect with a camera. Some visually based SHM incorporating drones is researched [85]-[87].

The momentousness of evolving a smart-city is becoming more and more vital. The use of sensors is one aspect with which this could be made possible. Using a large number of sensors is termed as multi-functional sensors. As stated in a previous section, it has been proved experimentally that the impedance signatures during the EMI technique differ with temperature changes. This gives the EMI technique the possibility of detection of damage simultaneously to determine the temperature of the host system.

9. CONCLUSIONS

Each nation spends a lot of money in the construction. All the civil structures play an important role in the lives and in the development of residents residing in a country. Any damage to such structures and systems effects the gross domestic production of the country, costs the loss of a lot of human lives and halts the growing development of the country as well as its residents. Structural strength decreases with continuous loading and environmental effects. Hence, the performance of the structure should be evaluated so as to check if the performance is satisfactory or not. By proper monitoring failure of the structures can be prevented.

This review engaged on the EMI technique and concentrated on the latest research in this field. There are still numerous problems in the implementation that need to be addressed like PZT's restricted sensing range, proper selection of the frequency interval, the need to account for temperature fluctuations, accurate statistical metrics, etc., must be overcome to monitor the damage. The EMI technique has great potential. However, because most of the experiments were carried out under laboratory conditions, future work should concentrate more on real life structures. The merging of the EMI technique with computational and FEM simulation is effectively working on bringing the technique near commercialization.

REFERENCES

[1] Aktan, A.E., Catbas, F.N., Grimmelsman, K.A. and Tsikos, C.J., "Issues in infrastructure health monitoring for management," Journal of Engineering Mechanics, 126(7), pp.711-724, 2000.

[2] Kessler, S.S., Spearing, S.M., Atalla, M.J., Cesnik, C.E. and Soutis, C., "Damage detection in composite materials using frequency response methods," Composites Part B: Engineering, 33(1), pp.87-95, 2002.

[3] Giurgiutiu, V., Redmond, J.M., Roach, D.P. and Rackow, K., "Active sensors for health monitoring of aging aerospace structures," Smart Structures and Materials 2000: Smart Structures and Integrated Systems (Vol. 3985, pp. 294-305). International Society for Optics and Photonics, June 2000.

[4] Lian, C., Sun, F.P. and Roger, C.A., "Coupled Electro-Mechanical Analysis of Adaptive Material System-Determination of the Actuator Power Consumption and System energy Transfer," J. Intell. Mater. Syst. Struct, 5, pp.12-20, 1994.

[5] Zhou, S., Liang, C. and Rogers, C.A., "Integration and design of piezoelectric patch actuators," Journal of intelligent material systems and structures, 6(1), pp.125-133, 1995.

[6] Bhalla, S. and Soh, C.K., "Structural health monitoring by piezo-impedance transducers. I: Modeling," Journal of Aerospace Engineering, 17(4), pp.154-165, 2004.

[7] Annamdas, V.G.M. and Soh, C.K., "Embedded piezoelectric ceramic transducers in sandwiched beams," Smart Materials and Structures, 15(2), p.538, 2006.

[8] Annamdas, V.G.M.; Soh, C.K.," Three-dimensional electromechanical impedance model for multiple

ITEE Journal
Information Technology & Electrical Engineering
ISSN: - 2306-708X

piezoceramic transducers—Structure interaction," J. Aerosp. Eng., 21, 35–44, 2008.

[9] Crawley, E. F. and de Luis, J. (1987), "Use of Piezoelectric Actuators as Elements of Intelligent Structures," AIAA Journal, 25(10), 1373-1385.

[10] Crawley, E. F. and Anderson, E. H. (1990), ''Detailed Models of Piezoceramic Actuation of Beams,'' Journal of Intelligent Material Systems and Structures, 1, 5-25

[11] Sirohi, J. and Chopra, I. (2000a), "Fundamental Behavior of Piezoceramic Sheet Actuators," Journal of Intelligent Material Systems and Structures, 11(1), 47-61

[12] Xu, Y. G. and Liu, G. R. (2002), "A Modified Electro-Mechanical Impedance Model of Piezoelectric Actuator-Sensors for Debonding Detection of Composite Patches," Journal of Intelligent Material Systems and Structures, 13(6), 389-396

[13] Ong, C. W., Yang, Y., Wong, Y. T., Bhalla, S., Lu, Y., and Soh, C. K. (2002), "The Effects of Adhesive on The Electro-Mechanical Response of A Piezoceramic Transducer Coupled Smart System." SPIE International Conference on Smart Materials, Structures and Systems, ISSS, Bangalore, 191–197

[14] Bhalla, S. and Soh, C. K. (2004c), "Impedance Based Modelling for Adhesively Bonded Piezo-Transducers," Journal of Intelligent Material Systems and Structures, 15(12), 955- 972

[15] Qing, X. P., Chan, H. L., Beard, S. J., Ooi, T. K. and Marotta, S. A. (2006), "Effect of Adhesive on Performance of Piezoelectric Elements Used to Monitor Structural Health," International Journal of Adhesion and Adhesives, 26(8), 622-628

[16] Han, L., Wang, X. D. and Sun, Y., (2008), "The Effect of Bonding Layer Properties on The Dynamic Behaviour of Surface Bonded Piezoelectric Sensors," International Journal of Solid and Structure, 45, 5599-5612.

[17] Dugnani, R. (2009), "Dynamic Behaviour of Structure-mounted Disk-shape Piezoelectric Sensors Including the Adhesive layer," Journal of Intelligent Material Systems and Structures, 20, 1553-1564

[18] . Park, S., Lee, J. J. Yun, C. B. and Inman, D.J. (2008), ''Electro-Mechanical Impedancebased Wireless Structural Health Monitoring Using PCA-Data Compression and k-means Clustering Algorithms,'' Journal Intelligent Material Systems and Structures, 19, 509- 520.

[19] Tinoco, H. A., Serpa, A. L. and Ramos, A. M. (2010), "Numerical Study of The Effects of Bonding Layer Properties on Electrical Signatures of Piezoelectric Sensors," Mecánica Computacional, XXIX, 8391-8409.

[20] Moharana, S., "Modelling of piezo-structure elastodynamic interaction through bond layer for electro-mechanical impedance technique" Ph.D dissertation, Dept. Civil Eng., IIT Delhi, 2012.

[21] Giurgiutiu, V., Reynolds, A. and Rogers, C.A., "Experimental investigation of E/M impedance health monitoring for spot-welded structural joints," Journal of Intelligent Material Systems and Structures, 10(10), pp.802-812, 1999.

[22] Sun, F.P., Chaudhry, Z.A., Rogers, C.A., Majmundar, M. and Liang, C., "Automated real-time structure health monitoring via signature pattern recognition," Smart Structures and Materials 1995: Smart Structures and Integrated Systems (Vol. 2443, pp. 236-247). International Society for Optics and Photonics, May 1995.

[23] Naidu, A.S.K., "Structural damage identification with admittance signatures of smart PZT transducers," Ph.D dissertation, 2004.

[24] Gopalakrishnan, N., "Piezoelectric sensor–based damage progression in concrete through serial/parallel multi-sensing technique," Structural Health Monitoring, 1, p.18, 2019.

[25] Bhalla, S., "A mechanical impedance approach for structural identification, health monitoring and non-destructive evaluation using piezo-impedance transducers," Ph.D dissertation, Nanyang Technological University, Singapore, 2004.

[26] PI Ceramics https://www.piceramic.com/en/

[27] Central Electronics Limited http://www.celindia.co.in/drupal7/

[28] Kaur, N. and Bhalla, S., "Numerical investigations on energy harvesting potential of thin PZT patches adhesively bonded on RC structures," Sensors and Actuators A: Physical, 241, pp.44-59, 2016.

[29] Smart Material corporation https://www.smart-material.com/index.html

[30] Yang, Y. and Divsholi, B.S., "Sub-frequency interval approach in electromechanical impedance technique for concrete structure health monitoring," Sensors, 10(12), pp.11644-11661, 2010.

ITEE Journal
Information Technology & Electrical Engineering
ISSN: - 2306-708X

[31] Keysight Technology https:// www.keysight. com/in/en/home. html

[32] Peairs, D.M.; Park, G.; Inman, D.J. "Improving accessibility of the impedance-based structural health monitoring method" J. Intell. Mater. Syst. Struct. 2004, 15, 129–139

[33] Xu, B.; Giurgiutiu, V. "A Low-Cost and Field Portable Electromechanical (E/M) Impedance Analyzer for Active Structural Health Monitoring" South Carolina University: Columbia, CA, USA, 2005

[34] Baptista, F.G.; Vieira Filho, J. "A new impedance measurement system for PZT-based structural health monitoring. IEEE Trans. Instrum". Meas. 2009, 58, 3602–3608

[35] Bhalla, S.; Gupta, A.; Bansal, S.; Garg, T. "Ultra low-cost adaptations of electro-mechanical impedance technique for structural health monitoring". J. Intell. Mater. Syst. Struct. 2009, 20, 991–999

[36] Panigrahi, R.; Bhalla, S.; Gupta, A. "A low-cost variant of electro-mechanical impedance (EMI) technique for structural health monitoring". Exp. Tech. 2010, 34, 25–29

[37] Mascarenas, D.L.; Todd, M.D.; Park, G.; Farrar, C.R. "Development of an impedance-based wireless sensor node for structural health monitoring". Smart Mater. Struct. 2007, 16, 2137

[38] Perera, R.; Pérez, A.; García-Diéguez, M.; Zapico-Valle, J.L. "Active Wireless System for Struct. Health Monitoring. Applications". Sensors 2017, 17, 2880

[39] Freitas, E.S.; Baptista, F.G. "Experimental analysis of the feasibility of low-cost piezoelectric diaphragms in impedance-based SHM applications. Sens. Actuators" A Phys. 2016, 238, 220–228

[40] Annamdas, V.G.M.; Soh, C.K. "Load monitoring using a calibrated piezo diaphragm based impedance strain sensor and wireless sensor network in real time". Smart Mater. Struct. 2017, 26, 045036

[41] Budoya, D.; Castro, B.D.; Campeiro, L.; Silveira, R.D.; Freitas, E.D.; Baptista, F. "Analysis of Piezoelectric Diaphragms in Impedance-Based Damage Detection in Large Structures". Proceedings 2018, 2, 131

[42] Park, S.; Yun, C.B.; Inman, D.J. "Structural health monitoring using electro-mechanical impedance sensors". Fatigue Fract. Eng. Mater. Struct. 2008, 31, 714–724

[43] Min, J.; Park, S.; Yun, C.B.; Song, B. "Development of a low-cost multifunctional wireless impedance sensor node". Smart Struct. Syst. 2010, 6, 689–709.

[44] Ursu, I.; Giurgiutiu, V.; Toader, A. "Towards spacecraft applications of structural health monitoring". INCAS Bull. 2012, 4, 111

[45] Rabelo, D.S.; Tsuruta, K.M.; de Oliveira, D.D.; Cavalini, A.A.; Neto, R.F.; Steffen, V. "Fault Detection of a Rotating Shaft by Using the Electromechanical Impedance Method and a Temperature Compensation Approach". J. Nondestruct. Eval. 2017, 36, 25

[46] Faria, C.T.; Owen, R.B.; Inman, D.J. "Macro-fiber composites performance under thermal cycling for impedance-based SHM applications". Act. Passive Smart Struct. Integr. Syst. 2014, 9057, 905726

[47] Tian, Z. "Guided Wave Based Integrated Integrated Structural Health Monitoring and Nondestructive Evaluation". Ph.D. Thesis, University of South Carolina, Columbia, SC, USA, 2015

[48] Wilkie, W.K.; Bryant, R.G.; High, J.W.; Fox, R.L.; Hellbaum, R.F.; Jalink, A.; Little, B.D.; Mirick, P.H. "Low-Cost piezocomposite actuator for structural control applications. Smart structures and materials 2000: Industrial and commercial applications of smart structures technologies"+. Int. Soc. Opt. Photonics 2000, 3991, 323–335

[49] Lalande, F., "Modeling of the induced strain actuation of shell structures," Ph.D dissertation, Virginia Tech, 1995.

[50] Bhalla, S., "Smart System Based Automated Health Monitoring of Structures," M.Eng Thesis, Nanyang Technological University, Singapore, 2001.

[51] Lim, Y.Y., "Structural identification by smart materials Final Year Report Nanyang Technological University," 2004.

[52] Bhalla, S., "A mechanical impedance approach for structural identification, health monitoring and non-destructive evaluation using piezo-impedance transducers," Ph.D dissertation, Nanyang Technological University, Singapore, 2004.

[53] Liu, W. and Giurgiutiu, V., "Finite element simulation of piezoelectric wafer active sensors for structural health monitoring with coupled-filed elements," Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2007 (Vol. 6529, p. 65293R). International Society for Optics and Photonics, April 2007.

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

[54] Yang, Y., Liu, H., Annamdas, V.G.M. and Soh, C.K., "Monitoring damage propagation using PZT impedance transducers," Smart Materials and Structures, 18(4), p.045003, 2009.

[55] Djemana, M. and Hrairi, M., "Modelling and simulation of impedance-based damage monitoring of structures," Int. J. Simul. Model, 15(3), pp.395-408, 2016.

[56] Naidu, A.S., "Electromechanical admittance signature analysis of piezo-ceramic transducers for NDE," Materials Today: Proceedings, 5(9), pp.19933-19943, 2018.

[57] Moharana, S. and Bhalla, S., "Numerical investigations of shear lag effect on PZT-structure interaction: review and application," Current Science, pp.685-696, 2012.

[58] Naidu, A.S., "Admittance Response of PZT Transducers Bonded to a Structural Member Subjected to External Loading," International Journal of Emerging Technologies and Innovative Research Vol.4, Issue 12, page no.542-551, 2017.

[59] Park, S., Ahmad, S., Yun, C.B. and Roh, Y., "Multiple crack detection of concrete structures using impedance-based structural health monitoring techniques," Experimental Mechanics, 46(5), pp.609-618, 2006.

[60] Li, F. and Li, G., "August. Application of ANSYS APDL in the Design of Piezoelectric Transducer," International Conference on Advanced Engineering Materials and Technology. Atlantis Press, 2015.

[61] Annamdas, V.G.M., "Facts of piezo impedance technique in crack propagation studies for an engineering structure," International Journal of Aerospace Sciences, 1(2), pp.8-15, 2012.

[62] Memmolo, V., Elahi, H., Eugeni, M., Monaco, E., Ricci, F., Pasquali, M. and Gaudenzi, P., "Experimental and numerical investigation of PZT response in composite structures with variable degradation levels," Journal of Materials Engineering and Performance, 28(6), pp.3239-3246, 2019.

[63] Hamzeloo, S.R., Shamshirsaz, M. and Rezaei, S.M., "Damage detection on hollow cylinders by electro-mechanical impedance method: experiments and finite element modelling," Comptes Rendus Mécanique, 340(9), pp.668-677, 2012.

[64] Kralovec, C., Schagerl, M. and Mayr, M., "July. Localization of damages by model-based evaluation of electro-mechanical impedance measurements," Proceedings of the 9th European Workshop on Structural Health Monitoring EWSHM], The e-Journal of Nondestructive Testing (Vol. 23), 2018.

[65] Powelson, T., "A study into the application of piezoelectrics to modify ankle torques in active prosthetic feet using finite element analysis," Ph.D dissertation, 2012.

[66] Giurgiutiu, V.; Kropas-Hughes, C.V. "Comparative study of neural network damage detection from a statistical set of electro-mechanical impedance spectra". Smart Nondestruct. Eval. Health Monit. Struct. Biol. Syst. II Int. Soc. Opt. Photonics 2003, 5047, 108–120

[67] Oh, T.K.; Kim, J.; Lee, C.; Park, S. "Nondestructive concrete strength estimation based on electro-mechanical impedance with artificial neural network". J. Adv. Concr. Technol. 2017, 15, 94–102

[68] Min, J.; Park, S.; Yun, C.B.; Lee, C.G.; Lee, C. "Impedance-based structural health monitoring incorporating neural network technique for identification of damage type and severity". Eng. Struct. 2012, 39, 210–220

[69] Na, S.; Lee, H.K. "Neural network approach for damaged area location prediction of a composite plate using electromechanical impedance technique". Compos. Sci. Technol. 2013, 88, 62–68

[70] Palomino, L.V.; Steffen, V.; Finzi Neto, R.M. "Probabilistic neural network and fuzzy cluster analysis methods applied to impedance-based SHM for damage classification". Shock Vib. 2014

[71] Tabrizi, A., Rizzo, P. and Ochs, M.W., "Electromechanical impedance method to assess dental implant stability," Smart Materials and Structures, 21(11), p.115022, 2012.

[72] Talakokula, V., Bhalla, S. and Gupta, A., "Monitoring early hydration of reinforced concrete structures using structural parameters identified by piezo sensors via electromechanical impedance technique," Mechanical Systems and Signal Processing, 99, pp.129-141, 2018.

[73] Annamdas, V.G.M.; Yang, Y., "Practical implementation of piezo-impedance sensors in monitoring of excavation support structures," Struct. Control Health Monit. 2012, 19, 231–245.

[74] Kim, J.T.; Park, J.H.; Hong, D.S.; Cho, H.M.; Na, W.B.; Yi, J.H., "Vibration and impedance monitoring for prestress-loss prediction in PSC girder bridges," Smart Struct. Syst. 2009, 5, 81–94.

Volume 9, Issue 5
October 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

[75] Bhalla, S.; Suresh, R., "Condition monitoring of bones using piezo-transducers," Meccanica 2013, 48, 2233–2244.

[76] Zuo, C.; Feng, X.; Zhang, Y.; Lu, L.; Zhou, J., "Crack detection in pipelines using multiple electromechanical impedance sensors," Smart Mater. Struct. 2017, 26, 104004.

[77] Liu, P.; Wang, W.; Chen, Y.; Feng, X.; Miao, L, "Concrete damage diagnosis using electromechanical impedance technique. Constr. Build. Mater," 2017, 136, 450–455.

[78] Dixit, A.; Bhalla, S., "Prognosis of fatigue and impact induced damage in concrete using embedded piezo-transducers," Sens. Actuators A Phys. 2018, 274, 116–131.

[79] Ai, D.; Luo, H.; Wang, C.; Zhu, H., "Monitoring of the load-induced RC beam structural tension/compression stress and damage using piezoelectric transducers," Eng. Struct. 2018, 154, 38–51.

[80] Yang, Y.; Lim, Y.Y.; Soh, C.K. Practical issues related to the application of the electromechanical impedance technique in the structural health monitoring of civil structures: I. Experiment. Smart Mater. Struct. 2008, 17, 035008.

[81] Sun, F.P.; Chaudhry, Z.; Liang, C.; Rogers, C.A. Truss structure integrity identification using PZT sensor-actuator. J. Intell. Mater. Syst. Struct. 1995, 6, 134–139.

[82] Park, G.; Kabeya, K.; Cudney, H.H.; Inman, D.J. Impedance-based structural health monitoring for temperature varying applications. JSME Int. J. Ser. A Solid Mech. Mater. Eng. 1999, 42, 249–258.

[83] Bhalla, S. and Bajaj, S., 2008. "Bone characterization using piezotransducers as biomedical sensors". Strain, 44(6), pp.475-478.

[84] Srivastava, S., 2018. "Bio-medical diagnosis of bones through collocated action of shape memory alloy (SMA) actuators and piezo sensors". Ph.D dissertation, Dept. Civil Eng., IIT Delhi, 2018.

[85] Ham, Y.; Han, K.K.; Lin, J.J.; Golparvar-Fard, M., "Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): A review of related works," Vis. Eng. 2016, 4, 1.

[86] Flammini, F.; Pragliola, C.; Smarra, G., "Railway infrastructure monitoring by drones," Proceedings of the International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), Toulouse, France, 2–4 November 2016; pp. 1–6.

[87] Reagan, D.; Sabato, A.; Niezrecki, C., "Unmanned aerial vehicle acquisition of three-dimensional digital image correlation measurements for structural health monitoring of bridge," Non-destructive Characterization and Monitoring of Advanced Materials, Aerospace, and Civil Infrastructure. Int. Soc. Opt. Photonics 2017, 10169.

AUTHOR PROFILES

Harkirat Kaur is a Research Scholar at Punjab Engineering College, Chandigarh. She has completed her M.Tech in Structures from Punjab Engineering College, Chandigarh in July 2018. Her Ph.D topic of research is assessment of R.C. beams using piezo transducers.

Dr. Sarita Singla is Professor at the Department of Civil Engineering, Punjab Engineering College, Chandigarh. She received Ph.D in Structures from Punjab Engineering College, Chandigarh in 2015. Her main research areas of interests are High Performance Concrete, Use of Admixtures in Concrete, Analysis and Structural Design of RCC, Steel Structures and Structural Health Monitoring.