APPLICATION OF EMI TECHNIQUE USING PIEZO ELECTRIC SENSORS

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ABSTRACT. Implementation of smart materials for non-destructive evaluation and testing (NDE & T) of civil, mechanical and aerospace structures have exponentially increased in the past few decades. Recent advent of electro-mechanical impedance (EMI) technique in the field of biomechanics and corrosion monitoring has been cost effective and time saving by implementation of a simple lead zirconatetitanate (PZT) patch. New applications have come up in the field of energy harvesting also. This paper deals with specific lab studies carried out in the above mentioned fields in the Smart Structures and Dynamics Lab (SSDL) IIT-Delhi. A brief mention of state-of-art of PZT as a transducer is presented. Feasibility studies and effectiveness of using PZT patches as a condition monitoring sensors in bio-mechanics, energy harvester in bridges and corrosion monitoring of reinforced concrete (RC) cubes and reinforced beams was covered. Data extracted through admittance signatures show promising results which is discussed in detail in the paper. In essence, a new spectrum of possibilities for application of PZT transducers in the field of structural health monitoring is studied.

Keywords: Corrosion assessment, Bio-mechanics, EMI technique, Energy harvesting, Piezo patches

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INTRODUCTION

Recent developments in structural health monitoring techniques and specifically electro-mechanical impedance (EMI) technique has proven to be effective, time saving and simple process for non-destructive evaluation (NDE). EMI technique today has expanded its horizons to many fields such as biomechanics, energy harvesting, corrosion monitoring etc., and has proven to be promising for the same. With increase in developments in the construction of roads, buildings and bridges and other infrastructural projects, in the NDE field, the current research is required for envisaging future application of this technique.

EMI is based on the direct and converse piezoelectric effect, which establishes a relationship between the mechanical properties of the structure and the electrical properties of the transducer attached to a host structure. PZT sensors used in the EMI technique are typically made of thin lead zirconatetitanate (PZT) ceramics of dimension 10 x 10 x 0.3 mm/ 5 x 5 x 0.2mm with the bottom electrode partially wrapped on the top electrode. In the EMI method, the integrity of the structure can be evaluated by the measurement and analysis of the electrical impedance derived from the PZT patch.. In EMI technique the PZT patches bonded on the structures are electrically excited at a higher frequency in the range of 30-400 kHz by an impedance analyzer or an LCR meter.

In this particular research work, an over view of the various applications of EMI technique is presented. In particular, all these studies have been carried out in the smart structures and dynamics laboratory (SSDL), department of civil engineering, Indian Institute of Technology, New Delhi, (India).

APPLICATION OF EMI TECHNIQUE IN ENERGY HARVESTING

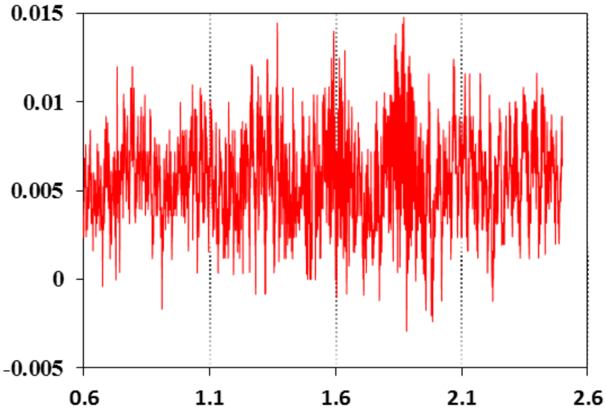
One of the potential application of the piezo patch is energy harvesting. Sensors can analyze the health of a civil infrastructure such as bridge from the obtain information. Currently these sensors rely on electro-chemical batteries as an energy source, which have limited lifespan and requiring periodical replacement or re-charging. Piezoelectric energy harvester (PEH) can be employed to power these sensors for structural health monitoring applications where solar power can be limited and even unavailable for embedded sensors. PEH have output voltage and simple structure in comparison to other harvesters which are based on different conversion mechanisms such as electrostatic and electromagnetic. For a piezoelectric plate of thickness *h*, the voltage generated across the terminals of the PZT patch can be expressed in terms of the strain S_1as :

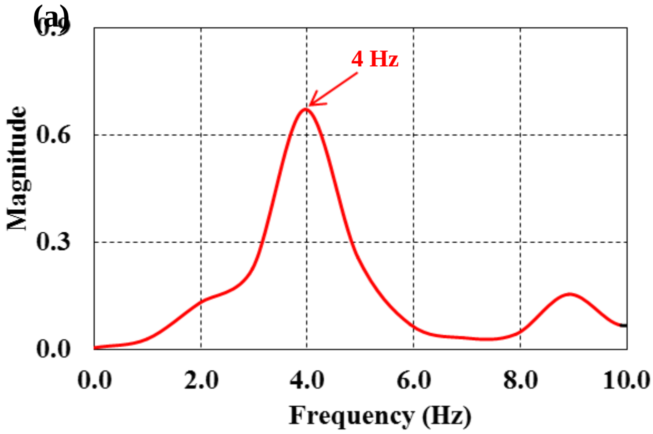
$$V = \left(\frac{d_{31}\overline{Y^E}h}{\overline{\varepsilon_{33}^T}} \right) S_1 \qquad (1)$$

where d_{31} is the piezoelectric strain coefficient providing coupling between the mechanical strain (along axis '1') and electric field E_3 (along axis 3), $\overline{Y^E} = Y^E(1 + j\eta)$ is the complex Young's modulus of elasticity of the PZT patch at constant electric field and $\overline{\varepsilon_{33}^T} = \varepsilon_{33}^T(1 - j\delta)$ the complex electric permittivity (in direction '3') of the PZT material at constant stress; with $j = \sqrt{-1}$, η and δ respectively denoting the mechanical loss and the dielectric loss factors of the PZT material. Piezoelectric materials are generally used in two modes i.e. $d_{31}$and d_{33}. In the d_{31} mode, the stress is applied along the length direction to produce voltage along the thickness direction. In the d_{33} mode, on the contrary, both the stress and the voltage act in the same direction, that is the thickness direction.

A number of studies have been reported on energy harvesting in bridge infrastructures. PEH converts the vibrations of the structure into electrical energy. Most of the developed PEHs are like resonator which works efficiently only when operate on the resonate frequency. Peigney and Siegert (2013) developed a cantilever type energy harvester. To extract the energy from the frequency band (15 Hz) of bridge vibrations, the resonant frequency in the developed energy harvester is kept 14.5Hz with proof mass of 12 g for tuning frequency it successfully produced a maximum power of 30 µW. Kim et al. developed a dual PZT cantilever with silicon mass using MEMS technology.

(a)





(b)

(c)

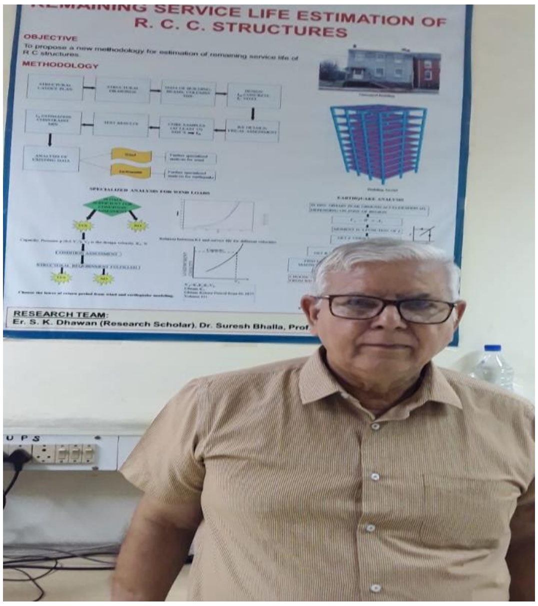
Figure 1 (a) General view of bridge
(b) Traffic induced vibration signal in time domain
(c) Same vibration signal in frequency domain

Numerical analysis was carried out using finite element analysis including a detailed parametric study. The prototype generated power output of 0.34 µW at 78.7 Hz under 0.5 g acceleration. In a subsequent study, Tufekcioglu and Dogan [3] described a parametric study of the design of piezoelectric energy harvester (PEH) and effect of stacking on the device performance. Cymbals with single-layer and two-layer stacked disks were used as transducers to develop PEH. A maximum power of 141.61 µW and 104.04 µW were obtained at 153 Hz and 166 Hz across 40 kΩ and 80 kΩ from respectively. It was concluded that stacked PZT generator harvests more energy than single layer transducer. For the SHM purpose the continuous external power source must be connected to the system. So to overcome this problem the concept of combined energy harvesting and SHM was introduced Kaur and Bhalla (2015). The main objective of the research was to utilize the same harvested energy for the SHM purposes thereby making the system.

The experimental research provided the feasibility of combined SHM and energy harvesting from the same PZT patch in the form of concrete vibration sensor (CVS) for RC structures. The power generated by the patch was determined as 1.417 µW. Balguvhar and Bhalla (2017) performed a basic field study conducted on a city flyover followed by laboratory based parametric study to highlight the typical practical issues associated with PEH from civil-infrastructures. The measurement shows that the natural frequency of the structure was 4 Hz. Other details of experiment can be found. If a PZT patch of 10×10×0.3 mm size were employed instead of accelerometers, computations show that it would generate a peak voltage of 0.736 V.

APPLICATIONS IN CORROSION OF REINFORCEDCONCRETESTRUCTURES

Rebar corrosion has become a very common cause of degradation in the reinforced concrete structures. It is most frequently the result of chloride induced breakdown of the passive film formed and embedded piezometric patches in diagnosing chloride induced corrosion from reinforced concrete structures.



Stages in Corrosion of Reinforcement

- Initiation
- Penetration of agents into the concrete
- Propagation

- Breakdown of protective later and onset of corrosion

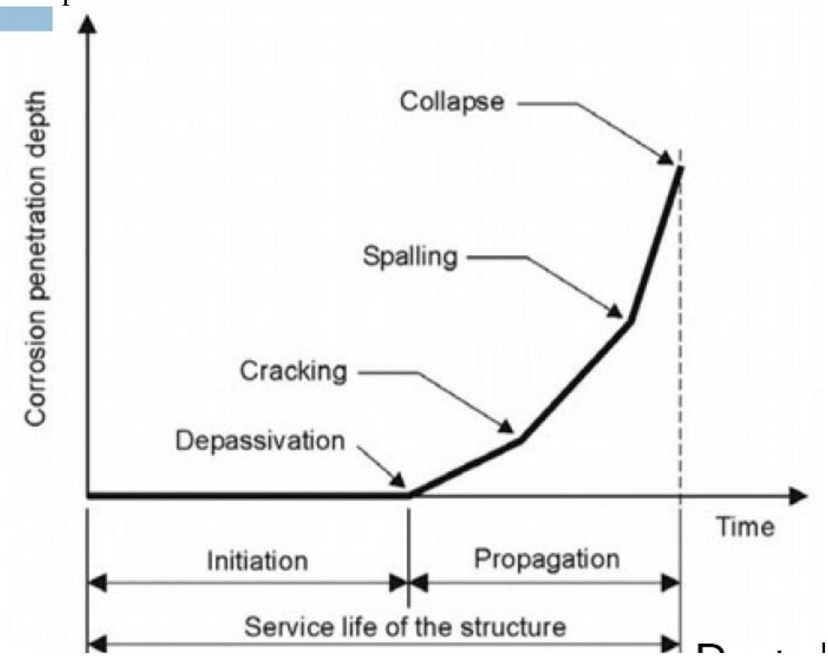


Figure 2 Showing the damage due to corrosion with respect to time

Passivating Film

At higher pH a dense passive layer is formed on embedded steel reinforcement.
Fe → Fe2+ + 2e-
$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2$
$Fe(OH)_2 + O_2 \rightarrow$ Fe2O_3 (γ-Fe2O_3)+ H2O

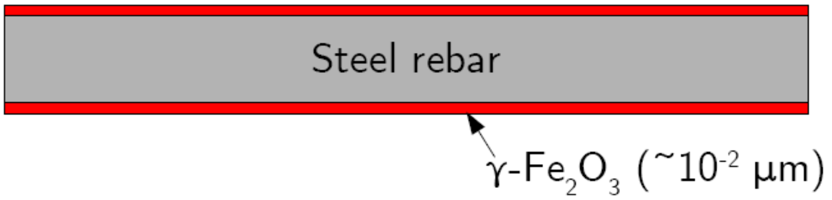


Figure 3 Rust formation

Corrosion of Steel in Concrete

- Corrosion is an electrochemical process
- Corrosion cells can be created due to dissimilar potentials arising from:
- Presence of dissimilar metals, e.g. steel and aluminum
- Presence of different concentrations of dissolved ions such as chlorides, etc.

Causes

- Carbonation or chlorides
- Galvanic coupling
- Stray currents
- Hydrogen embrittlement

Corrosion reaction

$$\text{Anode:}\quad Fe \longrightarrow 2e^- + Fe^{2+} \quad \text{(metallic iron)}$$

$$\searrow \quad FeO \cdot (H_2O)_x \ \text{(rust)} \quad \nearrow$$

$$\text{Cathode:}\quad \frac{1}{2} O_2 + H_2O + 2e^- \longrightarrow 2(OH)^-$$

The corrosion galvanic cell

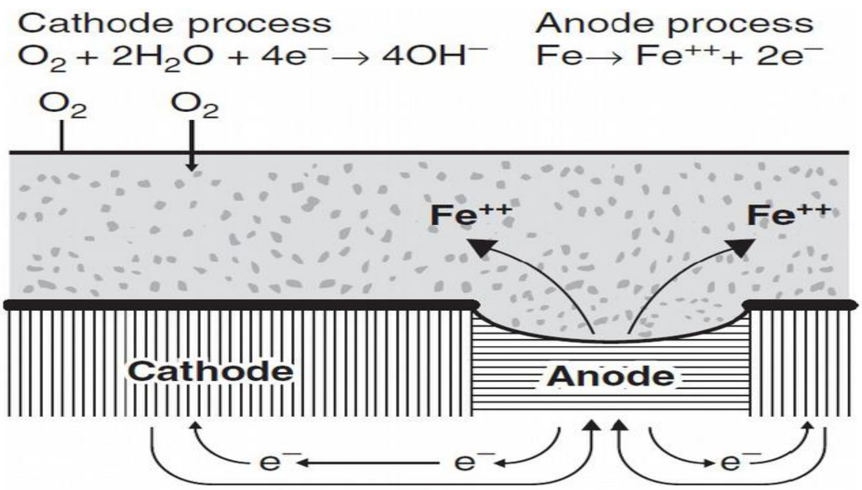


Figure 4 Electrochemical process

Expansion due to corrosion

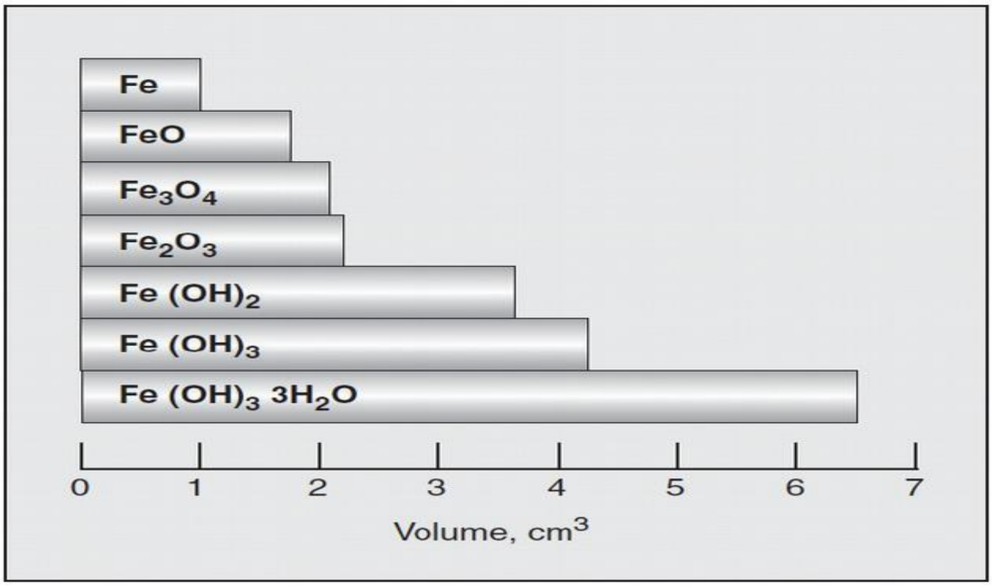


Figure 5 Expansion due rust formation

Corrosion of steel in concrete

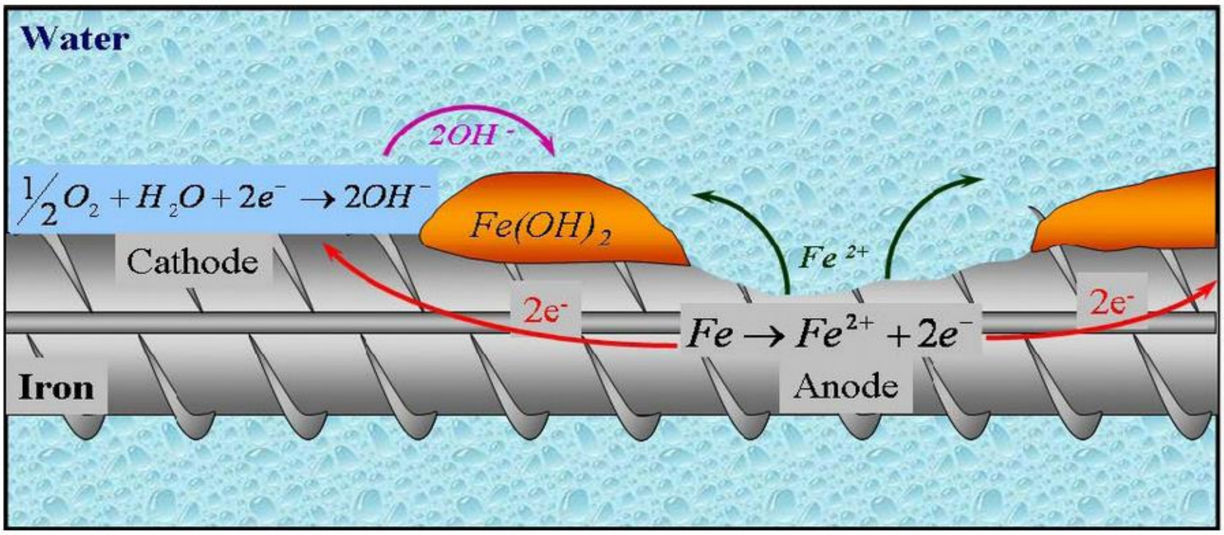


Figure 6 Basic reactions of corrosion in rebar

Above figure illustrates the basic reaction of corrosion, for which water and oxygen are needed at the cathode. Further chain of reactions ultimately leads to the formation of rust. The unhydrated ferric-oxide has the volume of twice of that of steel. When it becomes hydrate, it swells even more and become porous. As a result, the volume of steel concrete interface increases to about 6 to 10 times, subjecting the surrounding concrete in tension and ultimately leading to the cracking and spalling that we observe usual consequence of chloride induced corrosion. Talakokula et al.(2014). It is observed by applying EMI technique by piezo sensors in accelerated corrosion that there is significant loss of stiffness, mass and capacity of reinforced concrete beam element.

APPLICATIONS IN THE FIELD OF BIOMECHANICS

There is a high demand for non-invasive techniques in medical science for investigating the health of a patient while ensuring minimum discomfort and pain to the subject. Conventional techniques using strain gauges and accelerometers for biomedical structural health monitoring (BSHM) have been in practice for quite a number of years. Asundi and Kishen (2000) employed strain gauges and accelerometers for biomedical diagnostics. They performed *in vivo* strain and stress distribution in human dental supporting structures. Flavel et al. (2003) measured the relative movements of the head and the mandible (lower jaw or jaw bone) in human subjects walking and running on a treadmill at various speeds and inclinations.

Mostly, these methods involve bulky equipment and are time consuming. To overcome these limitations, extensive research for application of smart materials in BSHM is being considered. Smart materials, due to their low cost and flexibility can be a good alternative for serving the above purpose. Sharma et al. (2013) successfully investigated the use of flexible thin film PVDF-TrFE (polyvinyledenedifluoride-tetraflouroethylene) based pressure sensor for catheter applications. Dziuda et al. (2012) developed a device based on FBG sensors to monitor breathing and cardiac pulsations through the vibrations which occur during these processes.

In the recent years, electromechanical impedance technique (EMI), coming under the purview of NDT (non-destructive testing) methods has been extensively employed for monitoring of biomedical specimens. Ribolla and Rizzo (2014) successfully assessed the mechanical interlock of a dental implant with the surrounding bone, again using the EMI technique. Bhalla and Bajaj (2008) conducted an experiment on a chicken femur utilizing the PZT patches and successfully demonstrated their possibility as actuator-sensor pair to detect changes in mechanical properties of bones. Tinoco et al. (2017) explored the possibility of assessing stiffness variations in supporting substances of a human canine tooth with a bracket beam piezoelectric sensor using the EMI technique. Despite the undisputed success of the EMI technique for most routine engineering related structural health monitoring (SHM), the adhesive bonding of the PZT patch on the host structure has been a major limitation to its full-fledged application for biomedical health monitoring.

Srivastava et al. (2017) developed a proof-of-concept non-bonded piezo sensor (NBPS) configuration apt for EMI technique based BSHM. The NBPS configuration comprised of a thin metal strip with the piezo patch bonded to the centre of the strip. Proper mechanical interaction between the PZT patch and the bone was maintained by tightening of jubilee clamps upto a certain level of strain (316-350 µm/m). It was found that the NBPS configuration was quite effective in detecting damage/osteoporosis with respect to the DBPS even in the presence of skin layer.

CONCLUDING REMARKS

The paper gives a brief idea of different applications of EMI technique and suggests that SHM for future may be carried out by this simple yet effective method of interrogation. The EMI technique as discussed previously was successful in energy harvesting of civil structures. In this case the vibrations produced in bridges was harvested and an estimated power generated by the patch was determined as 1.417 µW. A peak voltage of 0.7 V was achieved. A brief review of corrosion process in RC structures was explained. As the PZT patch principles is based on change in impedance, it is suggested that for RC corrosion this technique would be effective in understanding the progression of corrosion when installed on rebar’s. In the field of bio-mechanics, a non-bonded variant was used non-bonded piezo sensor (NBPS). The study compared the effectiveness of the NBPS configuration with the conventional directly bonded piezo sensor (DBPS) configuration. It was found that the NBPS configuration was quite effective in detecting damage/osteoporosis with respect to the DBPS even in the presence of skin layer.

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