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TITLE: Application of Electromechanical Impedance Technique for Engineering Structures: Review and Future Issues

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Abstract: The recent advent of highly durable engineering materials and the advancement of latest structural design theories have made possible the fabrication of more efficient engineering structures. However, the safety and reliability of these structures remains the primary challenge and concern for engineers. Especially, for those structures which involve human traffic and huge investments such as the aerospace structures and bridges. Therefore, there is a compelling need to have high quality online structural health monitoring (SHM) of such structures. The development of a real-time, in-service and smart material based SHM method has recently attracted the interest of a large number of academic and industrial researchers. In the recent past, piezoceramic (PZT) transducer has evolved as an efficient smart material which is usually employed in electro mechanical impedance (EMI) and guided ultrasonic wave propagation techniques. In EMI technique, a PZT transducer interact with the host structure to result in unique health signature, as an inverse function of structural impedance, when it is subjected to high frequency structural excitations in the presence of electric field. Using the self actuating and sensing capabilities of PZT transducers, the EMI models attempted to detect loadings on, and damages in, the structures to be monitored. This paper reviews some of the advancements in the field of PZT based SHM made over the past two decades in engineering structures. This paper also provides an insight into the possible future work and improvements required for PZT based EMI technique.

Keywords: Smart sensor; structural health monitoring (SHM); piezoceramic (PZT) transducer; review and insight; safety and reliability; future applications.

INTRODUCTION

The recent advent of highly durable engineering materials (Winandy, 2002) and the advancement of latest structural design theories have made possible the fabrication of more efficient engineering structures. However, the safety and reliability of these structures remains the primary challenge and concern for engineers, especially those structures which carry human traffic such as the aerospace structures (NTSB, 2005; NMAB, 1996). A few of the aerospace failures which could have been prevented are:
a) Mid-flight accident of Boeing 737 plane of Aloha Airlines on April 28, 1988, in which entire fuselage panels were ripped apart against air pressure.
b) Mid-air crash of the American airbus, A 300-600 (Flight 587) on Nov. 12, 2001.
c) NASA space shuttle Columbia’s failure due to small undetected damage in its left wing on Feb. 1, 2003.
d) Bridge collapse in Minneapolis on Aug. 1, 2007.

Thus, there is a compelling need to have high quality online structural health monitoring (SHM) of modern or aged structures (Ruggiero et al., 2004; Ruggiero and Inman, 2005; Madhav and Soh, 2008). In the last two decades, the development of a real-time, in-service and smart material based SHM method has attracted the interest of a large number of academic, industrial and laboratory researchers in the world (Figure 1). In the recent past, piezoceric (PZT) transducer has evolved as an efficient smart material which can interact with the host structure to result-in a unique health signature, when subjected to high frequency structural excitations in the presence of electric field (Liang et al., 1994; Niezrecki et al., 2001; Park et al., 2003; Annamdas and Soh, 2007). The method of obtaining such signature, as an inverse function of structural impedance is termed as the electro mechanical impedance (EMI) technique (Liang et al., 1994).

![Figure 1](image)

**Figure 1.** Applications of PZT transducers for monitoring of engineering structures
(a) Civil engineering structure. (b) Aerospace structure.

These EMI models were attempted for detection of external loadings on (Abe et al., 2000; Ong et al., 2002; Mall, 2002; Annamdas et al., 2007) and damages in the (Sun et al., 1995; Giurgiutiu, and Rogers 1998; Yang et al., 2009) structures to be monitored. The applications of
PZT transducers are too abundant to list, however they are mainly used in the fields of ultrasonics (Yamashita et al., 2002), noise and vibration control (Wu et al., 1994), acoustic emissions, etc. (Prabakar and Mallikarjun 2005). The purpose of this article is to explore the importance and effectiveness of EMI in SHM. Furthermore, EMI has not seen many applications in real life structures even after its success in both laboratories and, preliminary practical applications in aerospace (for example, Chaudhry et al., 1995 monitored a Piper Model 601P airplane) and civil structures (for example, Yang et al., 2008a monitored an underground transit station in Singapore). The present form of EMI technology is still relatively new, and some of its impending issues like wiring of PZT transducer to signature acquisition instruments and frequency spectrum analysis still need to be fully addressed. Fortunately, these issues do not deter the use of EMI technique for monitoring engineering structures. Presently, rigorous research is on-going to address remote supply of electricity and to develop wireless sensing and actuating (David, 2006; Park et al., 2008). The initial breakthrough in EMI based wireless technology has confirmed the bright future for EMI.

This paper reviews major advancements in EMI during the past two decades and its application in Non Destructive Testing (NDE). This paper also provides an insight into the possible future work and improvements required for EMI technique.

DIFFERENT VARIETIES OF PZT MATERIAL

The ceramic PZT transducers are manufactured using solutions of lead zirconate and lead titanate, and are often mixed with other materials to obtain specific properties which when heated to high temperatures of around 800-1000°C, became perovskite PZT powder. The perovskite powder is then mixed with binder and sintered into the desired shapes (circular, ring, square, etc) of PZT transducers. In the poling process, an electric field is applied across the PZT transducer and the material became piezo electric (PE) in the plane normal to the poling direction but still remained mechanically isotropic (Bechmann and Fair, 1958).

In recent decades, new types of superior PE materials were developed in different forms, such as film, (Lee et al., 2000; Rong and Zhifei, 2008; Product Information Catalogue of Sensor Technology Ltd, 1995) paint, powder, single and multilayered fibre. They were also made available in several types, such as polyvinylidene fluoride and lanthanide-modified piezoceramic, depending on the chemical composition. However, most of these types are either
sensors or actuators but PZT is both actuator and sensor. The physical properties of the PZT transducers, as found in the literature are dependent not only on the manufacturing processes but also on the commercial manufacturers. It is reported that the properties of the PZT vary due to inhomogeneous chemical composition, mechanical differences during formation and the polarization process, and hence statistical variations are reported to be very common. Also, suppliers like the Mide group (Mide Group, 2008), Piezo technology (Product Information Catalogue of PI Ceramic, 2008); and piezo-kinetics group (Piezo Kinetics Group, 2008) provide different sets of properties for similar type of PZT. The main characteristic features of PZT are high elastic modulus, low tensile strength and brittleness.

**BACKGROUND OF EMI**

PZT transducers (see next section) in the presence of constant voltage signal (or electric charge), exerts constant force on the structure on which it is bonded. However in the EMI technique, the PZT transducer actuates harmonically (and imparts a harmonic force on the host structure) in the presence of electric field (varying voltage signal) to produce a structural response (comprising of peaks and valleys in ‘admittance versus frequency’ plots) which is known as electromechanical (EM) ‘admittance signature’. Here, the PZT transducer is either surface bonded or embedded inside the structure to be monitored. The EM admittance signature is a function of the stiffness, mass and damping of the host structure (Liang et al 1994; Sun et al., 1995), the length, width and thickness (Lee, et al 1997), and orientation of the PZT transducer (Wetherhold et al., 2003). This admittance signature comprises of conductance (G, real part of admittance) and the susceptance (B, imaginary part of admittance). The changes in the admittance signature, which is the inverse measure of mechanical impedance of the structure, are indicative of the presence of structural damages.

**MEASURING IMPEDANCE**

There are impedance analyzers such as those as shown in Figure 2. Agilent E4980A Precision LCR meter (Agilent E4980A, 2008), Wayne Kerr Precision and HP 4192A impedance analyzer (HP LF 4192A, 1996) are used to measure the PZT. The desired parameters such as impedance (Z), phase-angle, resistance, inductance, capacitance, conductance and susceptance can be obtained from these analyzers.
Figure 2. Impedance measuring instruments (a) HP 4192A analyzer. (b) Agilent E4980A LCR meter.

Most recently, a new method of impedance measurements utilizing a Fast Fourier Transform (FFT) analyzer and small current measuring circuit has been developed (Peairs et al., 2004). FFT analyzers, such as those used in modal analysis, are much more common and less expensive (less than $25,000 for a HP analyzer or less than $6,000 for a SigLab analyzer) than impedance analyzers. In addition, they often have the benefit of being portable and more importantly can be implemented on a computer chip, which is about the size of a postage stamp, making it possible to implement the new system in the field (Overly et al., 2008).

The electrical impedance of the bonded PZT transducer is equal to the voltage applied to the PZT transducer divided by the current passing through the PZT. An approximation of the impedance is generated by taking the ratio with the FFT analyzer of the voltage supplied to the circuit, \( V_i \), to the voltage, \( V_o \), across a sensing resistor, \( R_s \), in series with the PZT transducer, as depicted in Figure 3.

![Figure 3. Circuit for approximating PZT based EMI.](image-url)
The output voltage is proportional to the current passing through the sensing resistor when the sensing resistor is small (less than 200 ohms). The output is approximately the current passing through the PZT transducer if the sensing resistor was not included (as when measuring with a normal impedance analyzer). The circuit is described as $I = V_o / R_s$, where $I$ is the current passing through $R_s$. The approximated $Z = V_i / I = \left( \frac{V_o}{V_i} / R_s \right)$ but PZT is a capacitive element, the current passing through it increases with frequency. Conversely, at low frequencies the circuit has very high impedance. In this case an inverting amplification circuit can be used to provide a larger output voltage.

The measured impedance value of a component (or device or host structures) depends on several measurement conditions, such as the frequency of excitations, test signal level and manufacturing process of the PZT transducers. External factors like continuous loading, presence of acid or base, magnetic field, electric field, humidity, rain, heat, etc, and internal factors like electrical and mechanical properties of the PZT transducer will influence the measured impedance. The following describes several of the factors in detail.

**Test signal level (input / output)**

The applied test signal (AC) will affect the measurement results especially for ceramic capacitors because they are more dependent on the test signal voltage. This dependency varies depending on the dielectric constant (K) of the material used to make the ceramic capacitor. Figure 4 (Agilent Technologies, 2003) shows the plot of test voltage versus change in temperature ($\Delta C$). Assume that PZT can work effectively at room temperature, but if the temperature rises, then depending on K, the behavior of PZT changes (PI Ceramic, 2008). Non-linear variations can be observed if temperature exceeds room temperature.

![Figure 4](image.png)

**Figure 4.** Test signal level (AC) dependencies of ceramic capacitors.
PZT is a ceramic material which processes similar characteristic as shown in Figure 4, i.e.; its output measurement is affected by the test signal. When a sinusoidal excitation voltage (test signal) is applied to a PZT transducer (electrical excitation), which is bonded to the structure to be monitored will cause a corresponding mechanical excitation in the PZT transducer, which is then coupled (or transferred) into the structure through the bonding layer. The structure is excited based on the mechanical impedance of the structure and electrical impedance of PZT i.e. excitation is proportional to impedance. As a result of actuation, a corresponding strain is exerted on the PZT transducer. The structural strain will cause an electric charge output in the PZT transducer. The ratio between the applied voltage excitation and the charge output from the transducer, produces the electrical impedance measured by the impedance analyzer. The impedance analyzer measures mostly the frequency response function of the structure over the bandwidth of excitation.

**Frequency**

In order for an interrogation (test) signal (a function of frequency) to be sensitive to small cracks and damage, it is necessary for the wavelength (travelling wave) of any excitation to be smaller than the characteristic wavelength of the damage to be detected (Park et al., 2003). To facilitate the detection of small structural changes, a high frequency excitation must be used, thus, the EMI technique is generally carried out between 30-400 kHz (see later section on sensing range). This frequency range corresponds to wavelengths in aluminum which are less than 63 cm (David, 2006). Sun et al., 1995 recommended that the major vibration modes of the structure should be included for effective sensing range. The frequency range should include sufficient high number of resonance peaks (i.e. high mode density). Park et al., 2003b further recommended that the multiple frequency ranges containing 20-30 peaks should be chosen, because higher density of modes implies that there is a greater dynamic interaction over that frequency range. The high frequency range used for the EMI method has a number of advantages as outlined by Park et al., (1999, 2003b). Firstly, it makes the effective sensing area smaller to localize damage. Secondly, the localized damage area makes the PZT less dependent on the boundary conditions. Boundary conditions in real life structures are notoriously hard to characterize analytically, and tend to exhibit poor repeatability between structures (David, 2006). Lastly, the high frequencies make the sensor operation independent of any typical environmental
or operational vibrations. Generally, environmental and mechanical vibrations do not extend into tens to hundreds of kHz range, so they will have little effect on the operation of the EMI-based SHM system.

It should be noted that, if the host structure dimensions are smaller than the sensing range of the PZT transducer bonded on it, then the boundary conditions and the external vibrations can also influence the PZT based signatures (Esteban, 1996; Annamdas et al., 2007).

**Temperature, voltage and length of wire**

Several of the PZT parameters are temperature sensitive. Permittivity, piezoelectric charge constant, electromechanical coupling factor, capacitive characteristic and resonant frequency of the longitudinal oscillation are all affected by temperature variation. The overall effects of temperature on the EMI are generally a combination of uniform horizontal and vertical translations (Sun et al., 1995). Notably, the uniformity of the shifts is true when the frequency band is narrow. Park, 2000 investigated the effects of various operational conditions on the impedance method including external vibrations and temperature changes. Furthermore, when using a swept sine excitation, the impedance measurement equipment can be designed to filter out any excitation that does not occur at the current frequency point of interest. Raju, 1998 studied the effects of multiplexing (multiple PZT transducers), lead length, excitation voltage level, and ambient conditions. It was found that lead lengths less than 30 m have no adverse effects on the impedance method. In addition, the signal to noise ratio of impedance measurements could be improved by increasing the excitation voltage.

**Adhesive thickness**

Crawley and de Luis, (1987), Sirohi and Chopra, (2000) respectively modeled the actuation and sensing of generic beam elements by an adhesively bonded PZT transducer. Researchers (Xu and Liu, 2002; Bhalla and Soh, 2004) have suggested that the PZT transducer should be bonded to the structure using an adhesive of high shear modulus and smallest practicable thickness. Too low shear modulus of elasticity or too large thickness can produce erroneous or misleading results, such as over-estimation of peak frequencies or the dominance of PZT’s own frequencies. Furthermore, in order to minimize the influence of the bond layer, small-sized PZT transducers should be preferred for structural identification.
PZT dimensions and properties

The factors which influence the admittance signatures (plot of admittance versus frequency) in a significant way are length, width and thickness of PZT. The length and width influence the signature in horizontal plane whereas thickness in vertical plane (Esteban, 1996; Park et al., 2006; Annamdas, 2007) of admittance signature. Admittance signatures for few PZT transducers of different dimensions were experimentally obtained for the ‘free-free’ boundary condition (i.e. PZT is neither bonded on nor embedded inside any structure) by Annamdas and Soh, (2007) prior to the development of their 3D model. It was found that the decrease (or increase) in thickness for the same ‘length and width’ resulted an increase (or decrease) of amplitude for first major peak in admittance signature. Increase (or decrease) in ‘length and width’ for the same thickness resulted an (horizontal) shift of first major peak towards left (or right). The other factors which influence the impedance or admittance measurement are ‘the changes’ which arise in the PZT properties mainly due to deterioration of the PZT material during its life time, damping due to atmospheric factors like humidity, moisture and heat, acidic or alkaline attacks from sea water exposure (Yang et al., 2008a,b), and presence of electrical or magnetic zone (Lin, et al., 1988) near the PZT transducer (Annamdas and Soh, 2007). These property changes are key in damage or corrosion detection (Bedekar, et al., 2000) in an engineering structure.

BASIC PRINCIPLE OF PZT TRANSDUCERS

The basic constitutive relations for PE materials under small field condition are (IEEE, 1987; Sirohi and Chopra, 2000):

\[
\begin{bmatrix}
    [Direct] \\
    [Converse]
\end{bmatrix}
= [D] 
\begin{bmatrix}
    \epsilon^T \\
    d^d_{jm} \\
    d^c_{js} \\
    s^E \\
    T
\end{bmatrix}
\]

Figure 5 shows the direction of poling (or electric field), generated by a mechanical stress across the PZT transducer. The measured electrical charge is known as direct effect, used in sensor applications. Similarly, an electric field is applied across the PZT transducer to derive the induced mechanical strain in converse effect, used in actuator applications. Combinations of both effects are used in transducer applications where PZT acts both as an actuator and as a sensor.
Figure 5. A 3D piezoelectric material sheet.

\[ [D] \text{ (Coulomb/m}^2 \text{)} \text{ is the electric displacement vector of size (3 x 1), [S] is the dimensionless strain tensor of size (6 x 1), [E] (Volt/m) is the applied external electric field vector of size (3 x 1) and [T] (N/ m}^2 \text{)} \text{ is the stress tensor of size (6 x 1). Accordingly, } [\varepsilon^T] \text{ (F/m) is the dynamic dielectric permittivity tensor of size (3 x 3) under constant stress, } [d^d_{im}] \text{ (C/N) and } [d^e_{jk}] \text{ (m/V) are the PE strain coefficient tensors of sizes (3 x 6) and (6 x 3) respectively, and } [s^T] \text{ (m}^2/\text{N)} \text{ is the dynamic elastic compliance tensor under constant electric field of size (6 x 6). The superscripts ‘d’ and ‘c’ indicate the direct and the converse effects respectively. The superscripts ‘T’ and ‘E’ indicate the parameters that have been measured at constant stress and electric field respectively. Strain per unit electric field is the piezoelectric strain coefficient } d^e_{jk} \text{ and the electric displacement per unit stress is } d^d_{im} \text{ in the absence of mechanical stress and electric field, respectively which are numerically equal. In both } d^e_{jk} \text{ and } d^d_{im}, \text{ the first and the second subscripts denotes the direction of the electric field and the direction of the associated mechanical strain, respectively. Under static electric field, the crystal is free to deform and will not yield mechanical stress. Similarly, under short circuit condition, applied stress will not yield electric field (or surface charge).}

The matrix \([d^e_{jk}]\) depends on the crystal structure. For PZT transducer, as reported in the literature, it is given by:
\[
[d^c_{jk}] = \begin{bmatrix}
0 & 0 & d_{31} \\
0 & 0 & d_{32} \\
0 & 0 & d_{33} \\
0 & d_{24} & 0 \\
d_{15} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\] (2)

The coefficients \(d_{31}, d_{32}, \) and \(d_{33}\) (PE strain coefficients) are numerically equal to the normal strains in the directions 1, 2 and 3 respectively. The coefficient \(d_{15}\) relates the shear strain in the 1-3 directional plane to the field \(E_1\), and \(d_{24}\) relates the shear strain in the 2-3 directional plane to the electric field \(E_2\). In all poled piezoelectric materials, \(d_{31}\) and \(d_{33}\) are negative and positive, respectively (Bechmann and Fair, 1958; Benjeddou et al., 2000).

The compliance matrix is given as

\[
\begin{bmatrix}
S_{11}^E \\
S_{12}^E \\
S_{22}^E \\
S_{33}^E \\
S_{44}^E \\
S_{55}^E \\
S_{66}^E
\end{bmatrix}
\] = \begin{bmatrix}
\frac{1}{Y^E} & 0 & 0 & 0 \\
0 & \frac{1}{Y^E} & 0 & 0 \\
0 & 0 & \frac{1}{Y^E} & 0 \\
0 & 0 & 0 & \frac{1}{G^E} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\] (3)

From energy considerations, the compliance matrix is symmetric. Furthermore, for isotropic materials, there are only two independent coefficients, as expressed below (the remaining terms are zero):

\[
S_{11}^E = S_{22}^E = S_{33}^E = \frac{1}{Y^E} , \quad S_{12}^E = S_{13}^E = S_{21}^E = S_{31}^E = \frac{-V}{Y^E} , \quad S_{44}^E = S_{55}^E = S_{66}^E = \frac{1}{G^E} \] (4a)

where \(Y^E\) is the complex Young’s modulus of elasticity, \(G^E\) the complex shear modulus, and \(\nu\) the Poisson’s ratio. It should be noted that both \(Y^E\) and \(G^E\) are related as \(G^E = \frac{Y^E}{2(1+\nu)}\). For PZT transducer, the electric permittivity matrix and the stress vector are:

\[
[e^T] = \begin{bmatrix}
\varepsilon_{11}^T & 0 & 0 \\
0 & \varepsilon_{22}^T & 0 \\
0 & 0 & \varepsilon_{33}^T
\end{bmatrix}
\] and \(T = \begin{bmatrix}
T_1 & T_2 & T_3 & T_{13} & T_{12}
\end{bmatrix}^T\) (4b)
where i and j in $T_{ij}$ denote the electric field direction (if applied) and stress direction respectively.

**PZT-STRUCTURE INTERACTION MODELS**

Engineering structures can be classified into two categories based on their stiffness; those which are more and those which are less stiff than the PZT material. Additionally, two types of PZT attachments i.e. surface bonded and embedded PZT attachments are possible. From the authors past experiences, it can be stated that if PZT are embedded inside composite layers which are less stiff than PZT material, the chances of failure of PZT may be less. On the other side surface bonded PZT may be better employed for stiffer structures. However, there is no criterion for choice of attachment, it works on expediency. Researchers in the past tested the applicability of both surface bonded and embedded PZTs on same type of host structures (Park et al., 2000a,b). Several PZT-structure interaction models have been developed in the last couple of decades, first by Crawley and Luis, (1987) and Liang et al., (1994), and subsequently by Chaudhry et al., (1995), Sun et al., (1995), Park, (2000); Park et al., (2000a, 2000b); Giurgiutiu et al., (1999), Giurgiutiu et al., (2002), Zagrai and Giurgiutiu, (2001), Bandar and Abdulmalik, (2003), Bhalla et al., (2002a,b), Naidu, (2004), Annamdas and Soh (2006a,b), and Yang et al., (2009). However, in this section, only the basic PZT-structure interaction model developed by Liang et al (1994) is presented as follows.

**Basic PZT-structure interaction model**

For one dimensional (1D) configuration (Figure 6), the basic piezoelectric Equation (1) can be re-written as:

$$D_3 = \varepsilon_{33} E_3 + d_{31} T_1$$  

(5a)

$$S_1 = \frac{T_1}{Y^E} + d_{31} E_3$$  

(5b)

where $S_1$ is the strain in direction 1, $D_3$ the electric displacement over the PZT transducer, and $T_1$ the axial stress in direction 1. $Y^E = Y^E (1 + \eta j)$ is the complex Young’s modulus of elasticity of the PZT transducer at constant electric field and $\varepsilon_{33}^T = \varepsilon_{33}^T (1 - \delta j)$ is the complex electric permittivity (in direction 3) of the PZT transducer at constant stress. Here, $\eta$ and $\delta$
denote respectively the mechanical loss factor and the dielectric loss factor of the PZT transducer.

The 1D vibration of the PZT transducer is governed by the following differential equation, derived based on dynamic equilibrium of the PZT transducer (Liang et al., 1994).

\[ \frac{\partial^2 u}{\partial x^2} = \rho \frac{\partial^2 u}{\partial t^2} \]  

(6)

where \( u \) is the displacement at any point on the patch in direction 1. Solution of the governing differential equation by the method of separation of variables yields:

\[ u = (A \sin \kappa x + B \cos \kappa x) e^{i\omega t} \]  

(7)

where \( \kappa \) is the wave number, and is related to the angular frequency of excitation \( \omega \), density \( \rho \) and complex Young’s modulus of elasticity as \( \kappa = \omega \sqrt{\frac{\rho}{E_y}} \). Application of the mechanical boundary condition that at \( x = 0 \) (mid point of the PZT transducer), \( u = 0 \) yields \( B = 0 \).

Hence, the strain in PZT transducer and corresponding velocity are given by:

\[ S_1(x) = \frac{\partial u}{\partial x} = A e^{i\omega t} \kappa \cos \kappa x \quad \text{and} \quad \dot{u}(x) = \frac{\partial u}{\partial t} = A j \omega e^{i\omega t} \sin \kappa x \]  

(8)

Further, by definition, the mechanical impedance \( Z \) of the structure is related to the axial force \( F \) in the PZT transducer (at \( x = l \), where dimension of PZT is \( 2l \times w \times h \)) by:

\[ F_{(x=l)} = -Z \dot{u}_{(x=l)} \quad \text{i.e.} \quad whT_{1(x=l)} = -Z\dot{u}_{(x=l)} \]  

(9)

where the negative sign signifies the fact that a positive velocity causes compressive force in the PZT transducer (Liang et al., 1994).

Making use of Equation (5b) and substituting the expressions for the strain and the velocity
from Equation (8), the unknown constant \( A \) can be derived as:

\[
A = \frac{Z_a V_o d_{31}}{h_a K \cos (K l_a) (Z + Z_a)}, \quad \text{and} \quad Z_a = \frac{K w_a h_a Y_{31}^E}{(j \omega) \tan (K l_a)}
\]  

(10)

where \( Z_a \) is the short-circuited mechanical impedance of the PZT transducer.

This is defined as the force needed to produce unit velocity in the PZT transducer in short circuited condition (i.e. ignoring the piezoelectric effect) and ignoring the host structure. Where \( 2 l_a \times w_a \times h_a \) are the dimensions of PZT during short circuited condition. The electric current, which is the time rate of change of charge, can be obtained as:

\[
\bar{I} = \iint_A D_s dxdy = j \omega \iint_A D_s dxdy
\]  

(11)

Making use of the PZT constitutive relation, and integrating over the entire surface of the PZT transducer (-1 to +1), we can obtain an expression for the EM admittance (the inverse of EMI) as:

\[
\bar{Y} = G + jB = 2 \omega \frac{w l}{h} \left[ (\varepsilon_{33}^T - d^2_{31} \bar{Y}_E^E) + \left( \frac{Z_a}{Z + Z_a} \right) d^2_{31} \bar{Y}_E^E \left( \frac{\tan K d}{K d} \right) \right]
\]  

(12)

Figure 7 shows a typical plot of conductance (G) signature, for a PZT transducer bonded on a thin aluminum beam. The solid and dashed curves represent the undamaged state and the damaged state signature respectively, when a 5 mm hole is drilled in the aluminum beam (Liang et al., 1994; Naidu, 2004).

Figure 7. Conductance signatures for undamaged and damaged states (Frequency range: 100 -110 kHz) [Naidu 2004].
Some key developments in the field of EMI during last couple of decades

In 1980’s, researchers (Crawley, 1984, Crawley and de Luis, 1987) demonstrated the use of smart PZT transducer for SHM and vibration control, this was later verified by many researchers in later decades (Crawley and Anderson, 1990; Mayne and Dosch, 1994; Wu, et al., 1994; Schulz, et al., 1999; Inman, 2001; Kim, 2002). However, a basic 1D single PZT-structure interaction model was first developed by Liang et al., (1994) at the Centre for Intelligent Materials and Structures (CIMSS), Virginia Tech.; USA. The PZT transducer was assumed to be a thin bar undergoing axial vibration and interacting with the host structure. During the same period, Mayne and Dosch, (1994) presented a self sensing actuator system using PZT, which could act both as actuator and sensor. The sensing capability was found to be useful either for measurements of stress or strains. The actuator capability was found to be useful either as a force generator or positioning device, and are useful for purposes ranging from dynamic damping to shape control. The application of such a PZT transducer was employed in the EMI technique for SHM of a lab sized truss structure by Sun et al., 1995. The study was then extended to a large-scale prototype truss joint by Ayres et al., 1998. The EMI technique for 2D was also started during the same period by Zhou, Liang, and Rogers (1995, 1996). They developed an analytical model for a generic (square/rectangular) shape of PZT transducer using both the direct and cross impedances, which were related to the planar forces in directions 1 and 2 (Figure 5) and the corresponding planar velocities respectively. Recently, Giurgiutiu and Zagrai, (2005) developed an analytical model for 2D thin-wall structures, which predicts the impedance response considering axial and flexural vibrations of the structure and considers both the structural dynamics and the sensor dynamics. Moreover, calibration experiments were performed on circular thin plates.

It was in the year 2000 and after that significant proof of concept of the EMI technique for civil-structural components such as composite reinforced masonry walls, steel bridge joints and pipe joints were successfully applied (Park et al., 2000b). The technique was found to be very tolerant to small temperature fluctuations. Park, 2000 extended the EMI technique to high temperature applications (typically > 500°C), such as steam pipes and boilers in power plants. In addition, he also developed practical statistical cross-correlation based methods for temperature compensation. This paved the way for application of the technique to real situations, where the effects of damage and temperature are mixed. Soh et al., (2000) established the damage detection
and localization ability of these transducers for real-life reinforced concrete (RC) structures by monitoring a 5 m span RC bridge during its destructive load testing. Sensor positioning, damage localization and sensor validation criteria were outlined.

In 2001 and after, efforts were made to find alternate methods to record admittance signature without costly measuring instruments like impedance analyzers or LCR meters. Dosch et al., (2001) presented a practical implementation of the self-sensing actuator using ‘electrical bridge circuit’ to measure strain. The bridge circuit was found to be capable of measuring either strain or time rate of strain in the actuator. Giurgiutiu et al., (2002) combined the EMI technique with wave propagation approach for crack detection in aircraft components. While the EMI technique was employed for near field damage detection, the guided ultrasonic wave propagation technique (pulse echo) was used for far field damage detection.

In 2002, Inman et al., presented the concept of using the same hardware to simultaneously perform SHM and control. An aircraft panel often requires damping treatments in order to reduce fatigue. Here, an example of doing simultaneous health monitoring and control on a sample plate was demonstrated, which was a step ahead of previously developed technique of using PZT for both SHM and vibration control (Inman, 2001). Simultaneously, Abe et al., (2000) developed a stress monitoring technique for thin structural elements (such as strings, bars and plates) by applying wave propagation theory to the EMI measurement data in the moderate frequency range (1-10 kHz). This was again a step ahead of previously developed strain measuring technique (Peairs et al., 2004). Even though researchers like Abe et al., (2000); Ong et al., (2002) worked on stress identifications in structures, these studies have not fully focused on load identification and increase in magnitudes (Mall, 2002; Annamdas et al., 2007) and their characteristic behavior for 2D and 3D structures [see later section].

After 1994, every year resulted tremendous advancements in the filed of EMI technique, whereby proof of concept applications along with its integration with other NDE techniques were carried out in civil, mechanical and aerospace engineering structures. However, most research in was reportedly carried out by researchers in the USA. Integration of the EMI technique with wireless technology and development of stand-alone sensor cum processor cum transmission units based on MEMS and inter digital transducers (IDT) was also underway, which could enable large-scale instrumentation and monitoring of structures (Park et al., 2003b). In addition, several positive and negative aspects of the EMI technique were highlighted in their
numerous papers. Peairs et al., (2004) presented results from proof-of-concept tests on the launch pad's orbit access arm bolted connection, solid rocket booster support post, mobile launch platform heat shield and crawler transporter bearing. These tests showed that the EMI technique could provide an effective SHM solution to NASA's, 2008 ground structures. Recently, the search for effective alternate to the traditional impedance measuring instruments has become more rigorous. Peairs (2004) developed a novel low-cost and portable version of impedance analyzer, the major hardware used in the EMI technique, paving the way for cost-reduction (see Figure 3). David, (2006) presented an active-sensing wireless sensor node that can determine when a bolted joint connection has lost its preload. The sensor node was based on the EMI technique for application outside laboratory. However, this is in the preliminary stage which still needs much improvement for wide frequency range applications.

On the other hand, most mathematical modeling of PZT transducer with host structure was reportedly carried out in Asia. Soh and co-researchers (Annamdas and Soh, 2006, 2007, 2008; Bhalla and Soh, 2004a) have developed several 2D and 3D surface bonded and embedded PZT interaction models. The simplified plane stress based surface bonded PZT-structure interaction model (Bhalla and Soh, 2004b) is an improvement over the 2D model of Zhou et al., (1996). Applications of the simplified 2D model to concrete and aluminum specimens were presented by Bhalla, (2004). In the EMI models, usually the PZT transducers are bonded using adhesives. The adhesive forms a finitely thick, permanent interfacial layer between the host structure and the PZT transducer. Hence, the force transmission between the structure and the transducer occurs through the bond layer, via shear mechanism, invariably causing shear lag. The shear lag mechanism for 1D and 2D models were presented by Bhalla and Soh (2004a). Almost each year, several parameters which were previously neglected were considered in the later years by the researchers in their new models. For example, Cheng and Lin (2005a,b) developed a multiple PZT-structure interaction model considering ‘mass’ and optimal locations of the PZT transducers in the EMI formulations, which were previously neglected. This is a 2D model using multiple pairs of transducers bonded on the top and bottom of an aluminum plate. Giurgiutiu, (2007) summarized 1D (Liang et al., 1994) and 2D models (developed by Giurgiutiu group). Annamdas and Soh, (2007) presented mathematical models for both embedded and surface bonded PZT, considering longitudinal actuations along two principle directions (length and with of PZT) and the actuation along thickness (Annamdas and Soh, 2006; Giurgiutiu, 2007) of the PZT leading to
first 3D modeling of PZT transducer. This was later extended to 3D wrapped PZT -structure interaction model by Madhav and Soh, (2007), considering the mass influence of both the PZT transducer and adhesive layers. Moreover, this model also considered other limitations of the 1D and 2D models such as, restrictions on transducer shape, size and isotropy. Recently, Annamdas and Soh, (2008) presented a mathematical model for 3D multiple PZT interaction with structure in which a 3D wave propagation of multiple PZT transducers in the presence of sinusoidal voltage was analytical defined. The detailed analytical formulation, numerical implementation, matlab programming and experimental verification of all these models are presented by Annamdas (2007). These models express much thoroughly, the interaction mathematics of PZT, adhesive and host structure as compared to previous study by Bhalla, (2004).

It is apparent that SHM researchers are developing mathematical models superior than models of previous researchers. They are developing newer piezoelectric materials or/and applying new novel techniques like EMI for these newer materials, and are also integrating more than one techniques to develop more and more simple to use, efficient and robust SHM devices. They are focusing to apply EMI to newer fields like medical (Dugnani and Chang, 2008), biological and green materials like bamboo (Gaza et al., 2006). Additionally, integration of EMI with genetic algorithm (Xu et al., 2004), neural network (Lopes et al., 2000) etc., can be useful in NDE applications. Moreover, EMI can be combined with other NDE techniques to result in more effective NDE technique. More on this is presented in the following section.

**ISSUES AND FUTURE INSIGHT**

**Factors to consider for surface bonding or embedding PZT in host structure**

The PZT transducer should be non reactive, negligible stiffness and strength as compared to the host structure, so that it does not alter the dynamic properties of the host structure (Bechmann and Fair, 1958). It should also be kept away from atmospheric influences (like humidity, moisture and temperature) [Yang et al., 2008a,b], acidic/ alkaline attacks (due to rain or sea water exposures) and electrical or magnetic zone (Lin et al., 1988).

The surface bonded PZT transducer should have thin adhesive layer preferably 1/3rd of the thickness of PZT transducer (Bhalla and Soh, 2004a). The adhesive should be non-reactive with the underlying host structure. Life of the adhesive should be at least equivalent to that of the PZT transducer (Annamdas 2007).
The embedded PZT transducer must be properly isolated, using inert materials, to make it chemically stable (Paget et al., 2002). Moreover, they should withstand curing pressures and temperatures of the host material. They should be reliable during electrical and mechanical loading, and should withstand the combined mechanical and electrical cyclic loading (Mall and Hsu, 2000). The interface between the PZT transducer and the host structure needs to have reliable electrical conduction and bonding, hence needs sound interconnector (Hagood et al., 2000; Paget and Levin, 1999). Durability and protection from surface finish, vandalism and the environment are important features of embedded PZT transducers; however, they cannot be replaced if they are damaged. Hence robust embedded PZT transducers need to be developed which can withstand internal fluctuations of embeddable material and have life equal to that of the host structure.

Sensing region of PZT transducers

As stated previously, the sensing region of the PZT transducer is determined by the frequency range of excitation irrespective of the structural surface area to be monitored. Frequency range less than 400 kHz is ideal and any frequency range higher than 500 kHz is unfavorable. The frequency range below 30-70 kHz covers a larger sensing area. Unlike low frequency global excitations models (Pandey et al., 1991; Doebling et al., 1998), this high frequency based EMI models are limited to local area. The advantage of having localized sensing region is that the transducer is less sensitive to boundary condition changes as stated previously, which usually affect lower-order global modes. Moreover, unlike global vibration techniques which are highly susceptible to ambient noise, and tend to be less sensitive even to severe damages (Esteban, 1996), this EMI technique is robust enough to withstand unnecessary operational vibrations or noise disturbances (David, 2006) and are very sensitive (Park, et al., 2001; Bhalla, et al., 2002; Naidu, 2004) even for smaller degree of damages in the structure. However from various case studies and past experiences, the authors of this review paper found that for laboratory specimens where the host structure dimensions are much smaller than practical real-life structures, influence of the boundary conditions and external vibrations (like ultrasonic waves from Hz to MHz frequency range) can also affect the PZT based signatures (Annamdas et al., 2007). Moreover, for laboratory specimens (especially those made of metals), the whole structure usually comes under the sensing region of the PZT transducer and it can be monitored effectively.
Esteban, (1996) conducted a parametric study on the sensing region of the PZT transducer by considering various factors and geometries, such as mass loading effect (verified by Cheng and Lin, 2005a,b; Madhav and Soh, 2008), discontinuities in cross section, multi-member junctions, bolted structures (verified by Park et al., 2008 using wireless application), and energy absorbent inter layers. In general, sensing range of the PZT transducer is closely related to the material properties, geometry of host structure, frequency ranges of interrogation, and properties of the PZT transducers (Annamdas, 2007). According to book on damage prognosis published by Inman et al., (2005), and the knowledge acquired over many years, it has been estimated that the sensing region of a single PZT transducer can vary anywhere from 0.4 m (sensing radius) in composite structures to 2 m in simple metal beams. It should be understood that the waves which are generated due to actuation of PZT ceases to exist (or at least its amplitude reduces) beyond the sensing area.

Extensive numerical modeling based on the wave propagation theory has been performed by some researchers to identify the sensing region of PZT transducers (Esteban, 1996; Hu and Yang, 2007). If these models are coupled with the other local ultrasonic monitoring systems (such as wave propagation techniques like acoustic emissions as presented by Boller, 2002 or ultrasonics method as presented by Popovics et al., 2002) their capability to monitor the structure in real time can be enhanced.

**Sensing zone evaluation for optimization**

Every structure does have its weak/critical sections which require more attention than other sections. Especially like high stress zones, corrosion prone areas etc, these areas need to be monitored closely. It should be noted that the PZT actuations are along three directions (Annamdas and Soh, 2008) namely along length, width and thickness. Thus, depending on the geometry and material properties of the host structure, a thorough estimation of PZT sensing zone needs to be evaluated using these three types of actuations. Additionally, the optimal dimensions of the PZT and number of PZTs which need to effectively cover the critical area should be estimated. Length, width and thickness of PZT can be proportional to the host structural dimensions or it can be estimated based on the spacing between two critical sections in the structure. Over estimation of quantities of PZT can lead to wastage of money and on other
side, under estimation of quantities can risk the safety of structure. Future study should focus on optimal size, location and quantity of PZT transducers.

**EMI technique for co-existing load and damage in the structure**

PZT transducers are efficient in monitoring the loading on a structure in the absence of damages, or vice versa. The research using PZT based EMI for load applications are mostly limited to 1D structure (Abe, et al., 2000), but some work for 2D or 3D or complex structures are presented in Giurgiutiu, (2007).

Sun et al., (1995) found that the conductance signatures are good indicators of damage in the absence of external load on the structures. Other researchers (Bhalla, 2004) found that the susceptance signatures are good indicators of delamination in composite structures during the absence of external loadings. Similarly, in the absence of damages, PZT was found to be efficient in differentiating axial and transverse loads acting on the structure. Annamdas, et al., (2007) found that the conductance and susceptance are good indicators of axial and transverse loading respectively on the structures in the absence of damages. However, an important question arises which is to be addressed, is about the efficiency of EMI if both damage and loading co-exist in the structure.

**Remote sensing and wireless technology**

Park et al., (2003b) presented a practical method for an EMI based wireless SHM, which incorporated the principal component analysis (PCA)-based data compression and k-means clustering-based pattern recognition. An on-board active sensor system as shown in Figure 8, which consisted of a miniaturized impedance measuring chip (AD5933) and a self-sensing macro-fiber composite (MFC) patch (http://www.smart-material.com/MFC, 2009), was utilized as a next-generation toolkit of the EMI-based SHM system.

---

**Figure 8.** A miniaturized impedance measuring chip (AD5933) and a MFC patch.
The PCA algorithm was applied to the raw impedance data obtained from the MFC patch to enhance a local data analysis capability of the on-board active sensor system, maintaining the essential vibration characteristics and eliminating the unwanted noises through data compression. However, the frequency range of interrogation was limited to 10-100 kHz, which is much less than the frequency ranges of HP impedance Analyzers (5Hz-13MHz for 4192A and 100 Hz - 40 MHz for 4194 model) or Agilent LCR (20 Hz-2 MHz) meter. Most probably, this range can be increased in the next five years of research, and the initial breakthroughs in wireless technology had confirmed the bright future for EMI in SHM.

**Baseline-free signatures with new PE materials**

In EMI based SHM, to monitor any structure, the current standard procedure is to first obtain a baseline signature for the no-damage stage of the structure. This is then compared with later stages of EM admittance signatures of the structure to determine if there is any problem in the structure (see Figure 7). However, for the older existing structures, it is very difficult to obtain the no-damage baseline signature and hence, its comparison with later stage signatures is near impossible. Thus, a signature acquired from any structure at any considered time should have explicit or at least implicit information of the structure, and it should be possible to predict the condition of the structure without and need for comparison with no-damage baseline signatures. Thus, efforts of future research should focus on such a type of signatures either using EMI technique alone or in conjunction with other NDE techniques.

As stated earlier, the first practical application of PE was a sonar developed during 1910’s. For almost a century, efforts have been going on in developing newer and more superior PE materials. PZT transducers in the present form have ability to actuate in three dimensions (Jaffe, et al., 1971) and have three strain coefficients ($d_{31}$, $d_{32}$, and $d_{33}$) for applied electric field in thickness direction of the PZT transducers. The Macro-Fiber Composite (MFC) actuator (http://www.smart-material.com/MFC, 2009), developed by researchers at NASA, (2008) Langley Research Center (Wilkie, et al., 2000) has the capability to restrict actuations to either 1 or 2 directions. MFC actuators offer high performance and flexibility suitable for use in inflatable structures (Park et al., 2001b) or curvilinear surfaces as they are not as brittle as the PZT transducers. They are available in the markets as $d_{31}$ or $d_{33}$ types depending on the desired actuation direction. The restriction/control of actuation by such new generation transducers may
be used to monitor the health of structures without the need for baseline signature (Sohn, et al., 2007).

**Signal processing and damage assessment**

In the EMI based SHM, the key indicator of damage is the change in the admittance signature of the bonded PZT transducer. To characterize different types of damages, it is necessary to adopt statistical measures to quantify it. Samman and Biswas, (1994); Mays and Tung, (1992) presented a few pattern recognition techniques such as the signature assurance criteria (SAC), waveform chain code (WCC) technique and adaptive template matching (ATM) to quantify similar changes in acceleration signatures for a bridge structure. In the later years, more and more researchers have used (Guirgiutiu and Rogers, 1998) the root mean square deviation (RMSD) between the signatures of the two states as the suitable damage index. The RMSD index is presented as follows:

\[
\text{RMSD} (\%) = \frac{\sqrt{\sum_{i=1}^{N} (y_i - x_i)^2}}{\sum_{i=1}^{N} x_i^2} \times 100
\]  

(13)

where \(x_i\) and \(y_i\) (i = 1,2,3…N) are the signatures obtained from the PZT transducer bonded to the structure before (baseline or reference line) and after damage (change in structural state) has incurred.

Figure 9 illustrates an experimental RMSD result of a sample aluminum plate bonded with a PZT (PI Ceramic, 2008) to estimate the damage. Figure 9 (a) shows a sample plate, circular damage holes of diameter 5 mm were drilled one after another. At each damage state, signature for frequency range of 0-50 kHz was recorded and compared with the baseline state (no damage) signature. This comparison is in accordance with the Equation (13), and the subsequent result is shown in Figure 9 (b). The RMSD trend was found to increase as number of damage holes on plate increase.
Figure 9. Damage propagation studies (a) aluminium plate (b) RMSD verses increase in damage holes.

The damage index can also be defined in terms of Correlation Coefficient (CC). CC is equal to the covariance of two signature data sets divided by the product of their standard deviations, and is given as:

$$CC = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y}) \overline{\sigma_x \sigma_y}$$ (14)

where $\bar{x}$ and $\bar{y}$ are the mean values, and $\sigma_x$ and $\sigma_y$ are the standard deviations of the two signature data sets $x$ and $y$, respectively. CC measures the linear relationship between two signatures and is scaled to be independent of the unit of measurement. CC can be positive, negative or close to zero according to the correlation between the values of the two data sets. CC value is 1, when for all peaks in the undamaged state (baseline) signature, the damaged state signature also has peaks corresponding to the same frequency. When CC is -1, it indicates that at all the frequencies where the undamaged state signature has peaks, the damaged state signature has valleys, and vice versa. Thus, the lower the value of CC, the larger would be the deviation in the signatures, indicating greater degree of damage. CC has been widely used in statistical analysis of many engineering problems (Mays and Tung, 1992; Naidu et al., 2002a). Zagrai and Guirgiutiu, (2001) used Correlation Coefficient Deviation (CCD) indices, which is $(1-CC)^\alpha$ with different variations of the values of $\alpha$. For higher values of $\alpha$, the deviation of the index for different damage states is steeper.

Some other researchers in Asia preferred RMSD (Naidu, et al., 2002a,b) had over CC, SAC, WCC, ATM or CCD indices. Bhalla, (2001) in a detailed study on detection and characterization
of damage in concrete cubes compared the above techniques and observed that RMSD was the most suitable damage index to quantify structural damage of progressive severity. However, RMSD depends on the frequency range of excitations; i.e.; RMSD indices in the frequency range of 0-50 kHZ and 0-100 kHZ are different. Furthermore, Annamdas and Soh, (2007) found that RMSD index may not be that suitable for metals such as aluminum. This is because the frequency range of excitation should correspond to the wavelengths in the host structural materials, and a small 5% variation in the value of RMSD for concrete may be considered as severe (complete collapse of concrete structure) but not so for metal (only small crack in aluminum structure). Therefore, there is a gap for research to find better index or to modify RMSD to determine the generalized threshold limits for damage assessment of various materials.

Some other researchers in USA (CIMSS lab) and Brazil have developed a non-model based technique to localize and characterize structural damage by combination of the EMI and artificial neural network (Lopes Jr., 2000). To quantify the damage in the structures as similar to RMSD, multiple sets of artificial neural networks by utilizing measured electrical impedance were developed for various high frequency ranges. This combination technique could detect the damage in its early stage and also can estimate the nature of damage. Similar neural network technique was presented by Giurgiutiu and Zagrai (2005). They employed probabilistic neural network (PNN). EMI based analytical model for 2-D thin-wall structures was used to access local dynamics of structure and later statistical damage metrics like PNN are used to classify the EMI data and identify damage severity. Numerous statistical techniques have evolved to successfully quantify the damages in this decade. Park et al., (2005) presented an outlier analysis framework for EMI to quantify damage. In this, a modified auto-regressive model with exogenous inputs in the frequency domain was developed. The method of outlier analysis was then adopted to determine the damage state of a structure. Furthermore, they used extreme value statistics to establish proper confidence limits. It has been found that the proposed algorithm could assess the condition of a structure in a more quantifiable manner over the traditional impedance approaches. All these techniques can not fully satisfy the EMI researchers, newer and sophisticated statistical approaches are always going to be developed.

**Efficiency of PZT transducer**

Generally, when the embedded or surface bonded PZT transducer (Sun et al., 1995) is excited, it will extract the ‘structural responses’ and express them in conductance and susceptance
signatures. Structural response changes with any change in the frequency of excitation, and the peaks (or valleys) in any signatures are frequency dependent. Thus, the efficiency of any non-parametric index lies in its ability to indicate damage using both the changed peaks (or valleys) of signatures and the frequency range of excitation.

However, RMSD uses only the ‘changed peaks (or valleys)’ of signatures without using the frequency range of excitation. Thus, Annamdas and Soh, (2007) formulated the PZT efficiency factor to estimate the damage detection sensitivity of PZT transducer using the ‘changed peaks (or valleys)’ and frequency range of excitation.

The PZT efficiency factor (PEF) for chosen range(s) of frequency, is rationalized as:

\[
PEF = \frac{\frac{C_1 + C_2 + \ldots + C_K \ldots + C_N}{N} \sqrt{R_1^2 + R_2^2 + \ldots + R_K^2 \ldots + R_N^2}}{R_1 C_1 + R_2 C_2 + \ldots + R_K C_K \ldots + R_N C_N}
\]

where \( C_1, C_2 \ldots C_K \ldots C_N \) are the means of the frequency range (means of sum of upper and lower frequencies), and subscripts 1, 2, K and N are the number of considered frequency ranges as shown in Figure 10 (say for a total frequency range of 100 kHZ, if there are N=5 divisions with each division spanning 20 kHZ. i.e.; there will be 5 RMSD indices and 5 means, where R1-R5 are the RMSD indices in the range of 0-20 kHZ, 20-40 kHZ, 40-60 kHZ, 60-80 kHZ and 80-100 kHZ giving c1= 10, c2= 30, c3=50, c4=70 and c5=90).

\[
\text{Figure 10. Definition of PZT efficiency factor.}
\]

\( R_1, R_2, R_3 \) and \( R_4 \) are the RMSD values. For N=1, PEF becomes a ratio of RMSD to RMSD, that is, PEF= 1; thus cannot be used for comparison. Therefore, N > 1 is the necessary condition for the application of PEF; which is usually < 1. Moreover, lower value indicates higher sensitivity of the PZT transducer to detect damages in structures.

This PEF formula can be applied for quick assessment of PZT transducers (same dimensions)
manufactured by different suppliers to find the best PZT (sensitivity) among them.

For illustration of PEF, an example from literature (Annamdas, 2007) was considered. A PZT transducer (10 mm x 10 mm x 2 mm) was embedded in a composite aluminum plate of dimension 50 mm x 50 mm x 5 mm which includes two aluminum plates one each on top and bottom (dimension of 50 mm x 50 mm x 2 mm), and an epoxy layer in between. The PZT transducer was bonded on the centre of the epoxy layer. In summary, the PZT transducer was exactly at centre of the composite plate. A numerical study was carried out using 3D model of Annamdas, 2007 in such a way that 7 sets of properties of PZT were considered (say 1-7). This can be treated as seven different PZT transducers with seven different properties (Table 1) inside identical composite plates.

Here the question is that which PZT (among 1 to 7) is more efficient (sensitive) in detecting damage. Seven different conductance signatures were obtained for seven different property sets using 3D model as shown in Figure 11.

![Figure 11. Seven baseline conductance signatures for seven sets of PZT properties.](image-url)
Table 1. Seven Different variations and variations in properties of PZT transducer.

<table>
<thead>
<tr>
<th>Physical property</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>7800</td>
<td>7800</td>
<td>7800</td>
<td>7800</td>
<td>7800</td>
<td>7800</td>
<td>7800</td>
</tr>
<tr>
<td>Young’s modulus (N/m²) x 10¹⁰</td>
<td>6.667</td>
<td>6.667</td>
<td>6.667</td>
<td>6.667</td>
<td>4.5</td>
<td>6.667</td>
<td>6.667</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.43</td>
</tr>
<tr>
<td>Electric permittivity, $\varepsilon_{33}$ (farad/m) x 10⁻⁸</td>
<td>2.124</td>
<td>2.124</td>
<td>2.124</td>
<td>2.1</td>
<td>2.124</td>
<td>2.124</td>
<td>2.124</td>
</tr>
<tr>
<td>Piezoelectric strain Coefficient in direction X, $d_{31}$ (m/V) x 10⁻⁸</td>
<td>-2.10</td>
<td>-2.10</td>
<td>-2.10</td>
<td>-2.10</td>
<td>-2.10</td>
<td>-1.5</td>
<td>-2.10</td>
</tr>
<tr>
<td>Piezoelectric strain coefficient in direction Z, $d_{33}$ (m/V) x 10⁻¹⁰</td>
<td>4.50</td>
<td>4.50</td>
<td>4.50</td>
<td>4.50</td>
<td>3.0</td>
<td>4.50</td>
<td>4.50</td>
</tr>
<tr>
<td>Dielectric loss factor, $\delta$</td>
<td>0.015</td>
<td>0.020</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Mechanical loss factors $\eta$</td>
<td>0.023</td>
<td>0.023</td>
<td>0.013</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
</tr>
</tbody>
</table>

These baseline signatures alone cannot testify the sensing capability of the PZTs (1-7). Thus to evaluate sensitivity, a damage should be made on the structure and seven more signatures for seven different PZTs (1-7) should be obtained and compared with corresponding baseline signatures. The comparison between baseline and damaged state signature can be carried out using PEF. For this purpose, a damage of 20 mm long, 1 mm wide and 1 mm deep, was made as shown in Figure 12 (a) by reducing 50% of the stiffness and mass from the top aluminium surface elements of that region (20 mm x 1 mm x 1 mm) in the numerical modeling of composite plate (details are shown in Annamdas, 2007).
Again a 3D model was used to simulate 7 signatures for a damaged state of the composite. To carry out PEF, a minimum of two peaks in certain frequency ranges, two mean values ($C$) of these frequency ranges and RMSD indices (between baseline and damaged state signatures) for the same frequency ranges are needed. From Figure 11, there are about 8 peaks (P1-P8) in all the baseline signatures, but peaks P3 and P7 are of larger magnitude in the frequency ranges of 50-60 kHz and 75-85 kHz. The means of these frequency ranges are respectively $C_1 = 55$ and $C_2 = 80$. RMSD indices (say R1 and R2) in these ranges were computed between baseline and damaged state signatures, and final PEF were obtained using Equation 15. The PEFs were computed for all the seven sets of PZT properties as shown in Figure 12 (b).

The PEF values in Figure 12 (b) shows that the sensitivity is almost the same even though some signatures (Figure 11) had larger magnitude than other (say PZT 6 has larger conductance magnitudes than PZT 7). Thus, for sensing all these PZTs are identical.

However, more research on this need to be carried out for various peaks and broader frequency spectrum. A thorough optimization of frequency ranges and properties of PZT need to be studied before improving PEF. Future work need to be carried out so that it can readily provide the essential information for any lay person handling EMI based SHM.
There is also another criteria for the selection of a good PZT transducer, the algebraic sum of $d_{31}$ and $d_{33}$ should be maximum and, $\varepsilon_{33}$ and $\eta$ should be minimum this is a a lot of auto (Kumar, 1991). Future work can concentrate on fusing both properties of PZT with statistical indices like RMSD or PEF to provide guidelines to find efficient PZT or MFC transducers from among the many commercially available transducers.

**Compensation algorithms to counter the changes in PZT properties during its life time**

The atmospheric or surrounding factors can change the PZT properties like electric permittivity, Mechanical loss factor, Young’s modulus, PE strain coefficients and Poisson’s ratio (see Table 1). However, the manufacturers of the PZT transducers have more control on these properties. If they can manufacture excellent materials with superior PE qualities then the problem of deterioration can be addressed. At present many suppliers claim that the PZT life is in decades, and their deterioration rate is about 5% per decade (Mide Group, 2008; Product Information Catalogue of PI Ceramic, 2008; Piezo Kinetics Group, 2008). But, to safeguard PZT from external factors like humidity, heat etc.; PZT should be thoroughly protected using climatic resistant coatings or casings (Yang et al., 2008a,b). Else, compensation algorithms should be used to separate the influence of these factors on EM admittance signature (Park et al., 2003b). A thorough parametric study need to be carried out to evaluate the amount of compensation, which could be applied to admittance signatures.

**Integration and comparison with other NDE approaches**

The EMI technique monitors changes in the structural responses which are due to changes in the dynamic properties such as mass, stiffness and damping. This is similar to that of the global and local structural response methods such as ultrasonic technology, acoustic emission, magnetic field analysis, penetrant testing, eddy current techniques, X-ray analysis, impact-echo testing, global structural response analysis, and visual inspection. Some of these techniques like ultrasonic, eddy, acoustic emission methods have been shown to be effective in detecting damage at an early stage of occurrence. And some others are not so effective, however, irrespective of their effectiveness all these methods can be implemented in complementary with EMI methodology. Inspite of having many different genetic algorithms and neural network for identifying and localizing damage, the majority of these methods depend on vibration responses
or on the finite element analysis for damage diagnosis. Brief comparisons between the EMI and other NDE techniques can be found in the literature (Park et al., 2000a,b; Naidu, 2004). However, the EMI technique employs high frequency ranges of interrogation which are efficient in capturing localized damages either by using evolutionary programming (Xu et al., 2004; Yang et al., 2005) or by statistical indices (Hey et al., 2006). The structures to be monitored need not be restricted in services i.e. temporarily out of service, unlike when using the global structural or other high frequency vibration methods (Giurgiuțiu and Rogers, 1997). Moreover, skilled persons are not required to understand EM signatures and mere statistical estimations using say RMSD are enough. They need not require knowledge of wave propagation studies or structural characteristics. Global structural response methods or other high-frequency analysis methods may provide detailed information on anomalies in some structures, but these methods usually require complex instruments and wide-ranging skills to extract and interpret the measured data. Sensitivity of the EMI technique to detect minor defects is also comparable to that of the ultrasonic methods, however ultrasonic methods are unable to detect cracks perpendicular to the surface of wave propagation (Bechmann and Fair, 1958; Giurgiuțiu and Rogers, 1997; Lynch et al., 2004). In addition, costs of hardware can be reduced if more circuit-based and low-cost impedance analyzers are available (Peairs et al., 2004). Moreover, the sensing regions of the PZT transducers are much larger than those of the local ultrasonic or eddy current sensors, which are usually moved to scan over certain critical areas to detect anomalies in the structure to monitor (Park et al., 2003b).

It should be noted that PZT transducers in general and EMI technique in particular were also used in conjunction with other techniques (Park et al., 2001, 2000a,b; Naidu et al., 2002a,b; Koh et al., 1999) such as neural network, wireless technology, finite element analysis, evolutionary programming, ultrasonic methods or acoustic emission methods or any other wave propagation methods. These techniques including EMI are useful for health monitoring of civil (Yang, Annamdas, and Farrand 2008), aerospace (M7 aerospace service and innovative solutions for the aerospace industry, 2008; Giurgiuțiu, 2007), mechanical, medical, wooden (Gaza et al., 2006) and biological systems.

CONCLUSIONS
This paper reviewed some of the developments and applications of the EMI based SHM. The EMI technique provides several advantages over the traditional NDE approaches. First, because of the high-frequency range employed, the method is very sensitive to incipient damage in a structure and unaffected by changes in boundary conditions, loading, or operational vibrations. EMI technique can be used to quickly estimate the variations in the signatures. In future, statistical indices like RMSD can be used to trigger an alarm if the variation exceeds the threshold values. However, thorough investigations of this principle are still required. In future, newer PE materials like MFC (which are flexible) can be effective alternate to the brittle PZT transducer. In future, the EMI technique will also be better integrated with other techniques, especially wireless technology, for more effective SHM.

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