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Structural Health Monitoring Using Admittance Response of Piezoceramic Actuator Sensors

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***Abstract*—This paper delineates and reviews the recent technological developments in the field of Structural Health Monitoring (SHM) using the Electromechanical Impedance (EMI) technique. The EMI technique for SHM uses piezoelectric ceramic actuator sensors that are embedded in or surface-bonded to a structural member. The changes in the electrical admittance response over an ultrasonic frequency range of the actuator sensor thus mounted indicates the changes in the dynamic structural properties, such as mass stiffness and damping. These in turn indicate the state of damage in the structure. Owing to the EMI technique's high ultrasonic frequency range of operation, this technique has the capabilities of assessing incipient damages and structural changes locally without having to know the damage location a priori. This has potential capabilities of real-time, automated, and continuous structural health monitoring.**

***Keywords*—Structural Health Monitoring (SHM), Electromechanical Impedance (EMI) technique, Piezoelectric ceramic actuator sensors, Lead ZirconateTitanate (PZT), Non-destructive testing (NDT).**

I. INTRODUCTION

The economic and technological growth of a nation is reflected in the development of its infrastructure. The infrastructural development necessitates the complimentary support of the renewed maintenance, condition monitoring and retrofitting technologies. Most of the non-destructive testing (NDT) methods that are commonly adopted have a specific applicability [1], [2]. NDT methods are used for evaluation of the structural systems at the scheduled periods of inspection. These need some estimate of damage location based on expert knowledge and inferential insight of the maintenance inspector, even before testing. Further, the application of NDT methods may necessitate the portion of the structure, which needs to be inspected, to be rendered isolated and unfunctional during the duration of evaluation.

The Structural Health Monitoring (SHM) methodology aims at continuous monitoring and evaluation of the structural integrity adopting modern sensing technologies. The SHM methods do not require knowledge of the damage location a priori to the evaluation and can be applied even during the service period of the buildings, bridges or other infrastructure [3]. The electromechanical impedance (EMI) technique has come to light as a promising application for SHM [4]. The EMI technique extracts the impedance characteristics of the piezoelectric actuator/sensors that are surface bonded to or embedded into a structural member. There are many techniques using piezoelectric sensors for SHM, such as acoustic emission, ultrasonic pulse generation and more recently wave propagation techniques. This work primarily focuses on the developments made in the EMI technique for SHM.

II. HEALTH MONITORING METHODOLOGY

A. *Piezoelectric Property*

Piezoelectric materials are obtained in two forms (a) as ceramics such as the Lead Zirconate Titanate (PZT) and (b) as polymer films such as Polyvinylideneflouride (PVDF). Their unique property renders them in to a popular class of materials, called smart materials, intelligent materials or self-adaptive materials. Piezoelectric materials deform (strain) when an electric field is applied across their polarized ends and conversely, produce voltage across their poles when subjected to mechanical strain, as shown in Figure 1. This bifunctional property makes the piezoelectrics be used both as actuators and sensors. In some applications, one PZT ceramic chip is used as an actuator and another chip in pair is used as a sensor. The actuator sensor pair is used to generate lamb waves for structural diagnosis. However, in the EMI technique, the same piezoelectric ceramic chip acts as an actuator and the sensor.Thus, the PZT ceramic chip is also referred to, in such applications, as self-sensing actuators.

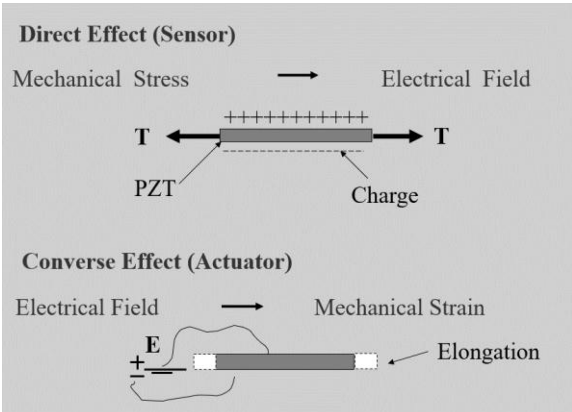

Figure 1: PZT sensor and actuator response properties

B. Electromechanical Impedance (EMI)*Technique*

The EMI technique exploits the characteristic features of the PZT ceramic actuator/sensors by subjecting them to alternating voltage source, which induces high frequency vibration to the PZT. The PZT, which is surface-bonded onto or embedded within the structural element, induces actuation in the structure, locally. The conductance signature, that is the real part of the electrical admittance (Y) of the PZT as a function of the excitation frequency, is extracted using impedance analyzers or LCR meters.

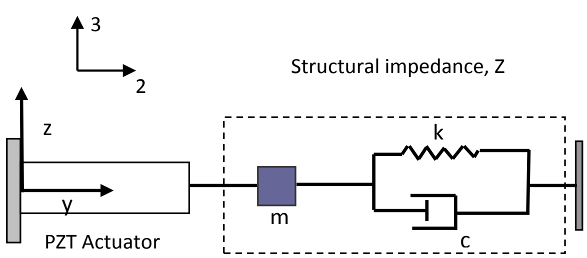

Figure 2: SDOF system actuated by a PZT actuator

The expression for the electrical admittance (inverse of impedance) of the PZT ceramic chip driving the host structure, modelled as a single-degree-of-freedom (SDOF) system as illustrated in Figure 2,has been derived and is available in the literature, which is expressed as [5]

$$Y = \omega j \frac{w_a l_a}{h_a}\left[\overline{\varepsilon_{33}^{T}} + \left(\frac{Z_a}{Z + Z_a}\right) d_{32}^2 \overline{Y_{22}^{E}} \left(\frac{\tan k l_a}{k l_a}\right) - d_{32}^2 \overline{Y_{22}^{E}}\right] \quad \ldots (1)$$

where w_a, l_a and h_a represent the PZT width, length and thickness, respectively. ω is the angular frequency of the applied alternating voltage, Z is the mechanical impedance of the host structure, and Z_a is the mechanical impedance of the PZT transducer, $\overline{\varepsilon_{33}^{T}}$ and d_{32} are piezoelectric constants and $\overline{Y_{22}^{E}}$ is the complex Young's modulus.

As observed in equation (1), there exists a coupling between mechanical impedances of the PZT and the host structure, in producing the output electrical admittance. Damage in a structure alters the mass, stiffness and damping characteristics locally, which alters the mechanical impedance of the host structure. The changes in the mechanical impedance of the structure, reflects in the changes in the electrical conductance (Re Y) of the PZT. This serves as the damage indicator. The same principle is applicable when modelling PZT-structure interaction in 2D and 3D. An example of experimentally obtained admittance signatures that get altered before and after damage occurrence is shown in figure 3 [6]. More specifically, the signatures are for conductance, the real part of the complex admittance. By signature, we mean the admittance response over a frequency range of actuation. These are similarto the frequency response functions used in the vibration analysis of structures, the only difference being the actuating frequency range.

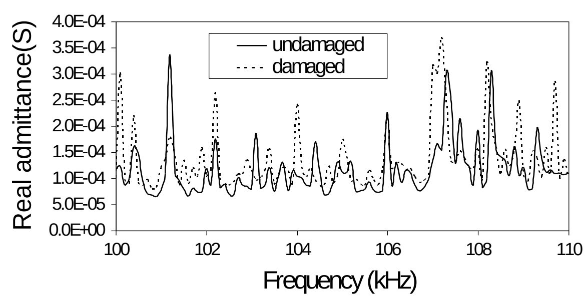

Figure 3. Real admittance signatures for damaged and undamaged states (in siemens)

III. TECHNICAL ASPECTS OF THE EMI TECHNIQUE

A. Test Equipment Requirement

The admittance signature of the PZT actuator sensor is usually acquired using commercially available impedance analyzers, such as HP 4192A impedance analyzer, Agilent E4980A Precision LCR meter, Wayne Kerr Precision impedance analyzer [4], [7].

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An image of such equipment is shown below in Figure 4. The commonly used electrical conducting wires are used to connect the PZT actuator sensor and the impedance analyzer. One end of the two wires is soldered to the two opposite electrodes of the PZT actuator sensor. The other ends of the wires are connected to the terminals of the impedance measuring equipment.

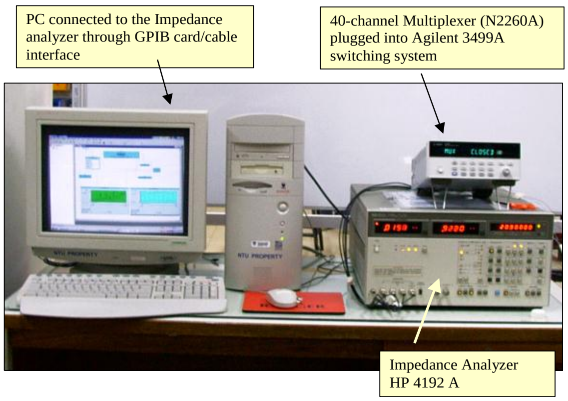

Figure 4: Typical Impedance Measuring Equipment [6]

B. Power Requirement

The impedance analyzer imposes an alternating voltage signal of 1 volts rms (root mean square) to the bonded PZT actuator sensor over the user specified pre-set frequency range. It has been observed that higher excitation voltage has no influence on the conductance signature, but might only be helpful in amplifying weak structural modes [8].

C. Influence of Adhesive

The adhesives usually used to bond the PZT actuator sensor chips on to the structure are epoxy resins. The adhesive hasto transfer the high frequency mechanical actuation of the PZT to the structure. Adhesive layer must also be a transparent via medium to allow coupling of the host structure with the PZT. Thus, epoxy used must be of high shear modulus after hardening and must be of smallest possible thickness for achieving uniform bonding. The effect of the adhesive layer on the quality of admittance signatures, both real part - conductance and the imaginary part – susceptance, have been extensively studied [9].

D. PZT Dimensions

Annamdas and Soh [10], [11] showed that the decrease in thickness for the same 'length and width' resulted an increase of amplitude for first major peak in admittance signature, and vice-versa. Increase in 'length and width' for the same thickness resulted a horizontal shift of first major peak towards left, and vice-versa.

E. Sensing Zone

The sensing radius of a typical PZT actuator sensor might vary anywhere from 0.4 m on composite materials structures to about 2m on metallic beams [7], [12].

F. Frequency Range of Actuation

The conductance signature of the PZT is acquired over a high frequency range in the pristine or 'healthy' state of the structure. Later, whenever desired to assess the structural health, the signature is extracted again and compared with the pristine signature. For effective detection of the changes in signatures appropriate frequency range may be chosen. Park and co-workers [13] recommended a frequency range from 30 kHz to 400 kHz for obtaining the admittance signatures of the PZT actuator sensors 5 to 15mm in size. A higher frequency range (>200 kHz) is favorable in localizing the sensing range, while a lower frequency range (<70 kHz) covers a large sensing area.

G. Damage Metrics

The prominent effects of structural damages on the conductance signature are the appearance of new peaks in the signature and lateral and vertical shifting of the peaks, which are the main damage indicators. Many pattern recognition techniques to quantify these variations have been reported in the literature, such as the root mean square deviation (RMSD), waveform chain code (WCC) technique, the signature assurance criteria (SAC), the adaptive template matching (ATM), relative deviation (RD), mean absolute percent deviation (MAPD), Coefficient of correlation (CC) and Covariance (Cov) [7], [8], [12]. These are all non-parametric and purely statistical damage metrics. Naidu and Soh [14], [15] demonstrated that purely statistical damage metrics do not capture the very important effects on structural dynamic parameters, such as the natural frequency, due to structural damages. The parametric metrics try to capture changes in natural frequency and modal parameters, and give better insight in identifying location as well as the severity of the damage.

H. Temperature Effects

The conductance signatures of the PZT actuator sensors are temperature sensitive. Thus, the effects on the signature due to damage and due to temperature exist simultaneously. This necessitates a method to decouple the two. Over a small frequency band, the overall effect of temperature has been observed to be a superposition of uniform horizontal and vertical translations of the signature [8].

This is different from the signature deviation resulting from any damages, which cause an abrupt and local variation. Thus, the effect due to temperature can be compensated with suitable corrections to the admittance signatures before going ahead for damage assessment [16].

IV. EMI Technique For SHM Applications

There have been numerous reports on successful proof-of-the-concept tests for damage identification in structures with the EMI technique [4], [13], [17].

The most prominent applications in localized damage identification have been reported on lab-sized truss structure, large scale prototype truss joint, steel bridge joints and pipe joints [18]–[20], RC Bridge of 5m span subjected to destructive flexural load test [21], in plain concrete structures[22], steel and aluminium plates [6] and aircraft panels and components [23], [24]. In all of these applications, it was shown that for the PZT sensor that was in a closer vicinity to the induced damage, the damage metrics estimating the changes in PZT conductance signatures were higher compared to the values for those PZTs that were far away from the location of the damage. Thus, by using an array of PZT actuator sensors in different critical locations of the structure will enable in localizing the damage occurrences for long term monitoring of structures. It has also been observed in some of the these works that the EMI conductance signatures are not affected by the mechanical noise due to random impacts or motions such as vehicular motions on bridges. This is because the operating frequency range in EMI technique is in the ultrasonic range (> 20 kHz), which the mechanical noise has much lower frequencies, usually.

The EMI technique has been used along with a damage prognosis model based on linear elastic fracture mechanics concept to estimate the remaining useful life of structure subjected to fatigue [25].

The EMI technique has also been used to monitor the axial and flexural stresses in beams to distinguish them from damage induced changes in the conductance signatures [26]–[29].

The EMI technique has been applied for monitoring initial hydration of concrete [30], [31] and strength gain during curing period [32], [33]. Extending the application of the method, the EMI technique has been successfully tested as a potential method for corrosion assessment of RC structures, which is a critical factor for its durability. Previous works on corrosion detection using EMI have also been reported in the work [34].

Even in the field of retrofitting and strengthening of structures, the EMI method has been applied for monitoring the debonding of CFRP laminates and FRP rebars [35], [36]. Use of embedded PZT actuator sensor as smart aggregate for concrete strength and health monitoring is also reported [37]–[40].

V. Technical Developments Of The EMI Technique

A. Miniaturization and low-cost variants of EMI technique

Typically, the impedance measuring devices, such as HP4192A/HP4194A impedance analyzers are used for extracting the admittance signature of the surface bonded or embedded PZT actuator sensors. The data is extracted into a computer via an I/O interface software. The main disadvantage of this equipment is it bulky size and difficulty in portability from one place to another for testing. Further, the impedance analyzer along with the test fixtures for PZT for EMI may cost about US $ 40,000 i.e. about 26 lakhs in INR. Further, the capabilities of the highly sophisticated impedance analyzers are highly under-utilized in the EMI technique. The cost of the PZT ceramic actuator sensors are in addition to the equipment, however the cost of a PZT ceramic actuator sensor piece is cheap, at around US $ 1, i.e. about 60 INR. Alternative to Impedance Analyzers, LCR meters have also been used along with proper test fixture for extracting the admittance signature of the PZT. LCR meter is a relatively less sophisticated instrument with lesser features than the impedance analyzer. However, its cost is also in the range of US $ 15,000 – 25,000 for a new piece, about 15 lakhs INR [17].

In an attempt to reduce the size of the equipment, Peairs and co-workers [41] developed a simplified miniature operational amplifier based turnkey device, that uses a digital signal analyzer with a FFT function (HP 35665 A). The circuit employed by Peairs and co-workers consisted of a small resistance (typically $<10\ \Omega$), connected in series with the PZT actuator sensor bonded to the structure to be monitored. This newly configured circuit along with the more commonly available Digital Signal Analyzer has been successfully demonstrated for structural damage identification applications. Further, the cost of this equipment is about US $ 15,000 – 20,000 less than the impedance analyzer. Giurgiutiu and Xu [42] also developed a field-portable small-sized impedance analyzer for EMI method.

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Panigrahi and co-workers [43] improvised on the method used by Peairs, by doing away with the FFT analyzer and instead using a function generator (Agilent 33220A) to generate the voltage signal. Agilent 54622D mixed signal oscilloscope was employed to measure the output voltage at each excitation frequency. The total cost of the equipment used was about $5000 only.

Bhalla and co-workers [44] proposed another system with still lower cost of about USD 2000, about 1.3 lakh INR . It utilized Agilent 34411A digital multi-meter and a very basic function generator. However, the system was limited in the sense that it only provided measurement of the magnitude of admittance and not the phase.

Kaur and co-workers [45] brought in another variation to the above hardware configuration set-up. The function generator is retained to generate the voltage signal. A new feature is that NI Express Chassis is used to measure output voltage at each excitation frequency and its phase lag with respect to the input voltage. The resulting admittance function is complex, quite akin to the measurement of the impedance analyzer.

B. Integration with Wireless Technology

It has been reported in the literature that the length of the wires connecting the PZT to the impedance measuring instrument can have adverse effect on the admittance signatures if the length of the wires exceeds 30 m [4]. Further, when considering mounting an array of sensors to a structure, managing all the wires becomes extremely cumbersome and confusing. Thus, researchers have made attempts to adopt wireless technology to overcome these issues.

One of the first attempts towards a wireless system for EMI was investigated by Mascarenas and co-workers [46], whodeveloped a portable, miniaturized and a low-cost impedance measurement chip. Its application was successfully tested in detecting load changes in a bolted frame structure. The wireless communication and local signal processing at the sensor node was investigated by integrating the device with a microprocessor and telemetry.

Incorporating the principal component analysis (PCA)-based data compression and k-means clustering-based pattern recognition, Park and co-researchers [47] developed an EMI-based wireless SHM technology. The hardware system consisted of a miniaturized impedance measuring chip (AD5933) and a self-sensing macro-fiber composite (MFC) patch.

While having many advantages, the limitation was that the frequency range of interrogation was restricted to 10-100 kHz, which is much less than the frequency ranges of HP impedance Analyzers (5 Hz to13 MHz for HP 4192A and 100 Hz to 40 MHz for HP 4194A model) or Agilent LCR (20 Hz to 2 MHz) meter.

Another such wireless active sensing system was developed by Grisso and co-researchers [48]. Overly and co-researchers at the Los Alomos National Laboratory, New Mexico, USA further developed a Wireless Impedance Device (WID 2.0) consisting of the previously used impedance measuring chip, microcontroller chip, wireless telemetry device and data storage chip all within a board of size 5.5 x 3.7 cm^2 [49]. This device was portable, operating at 2.8V and would take 6 seconds to measure four sensors with 100 points and four averages per point. The developments revealed good potential for the further development of the wireless technology.

Further developments of the battery powered based wireless sensor node for the EMI technique is adequately summarized by Annamdas and Radhika [17].

C. Energy Harvesting Units for EMI Technique

The continuous interrogation and monitoring requirements for the EMI method for a practical implementation of large scale SHM applications requires a constant power supply. In many cases, the remote and critical locations of a structure are inaccessible on a regular basis. To connect the PZT actuator sensors to the impedance measuring devices with long wire in those remote locations induces technical inaccuracies. On the other hand, using many sets of impedance measuring devices to access the PZT actuator sensors becomes very expensive and impractical. Wireless sensor nodes seem to be a workable solution. However, the wireless adaptations are all dependent of battery power supply, which is limited and can cause interruptions and discrepancies for long-term SHM applications.

Energy harvesting technologies could supplement the power requirements of the wireless system for EMI to further enhance its capabilities for real life applications. Annamdas and Radhika [17] have summarized the various developments in the energy harvesting technologies, based on tapping either solar energy or vibration energy, with the view of possible applications in the EMI method for SHM. Few attempts have been reported in this connection.

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A low power dependent and self-powered wireless EMI-based SHM sensor node using a Texas Instruments MSP430 evaluation board was developed [50]. The sensor node performs a SHM interrogation at pre-assigned intervals, and wirelessly transmits reports to the host computer. Consuming only 0.3 J per operation, it is easily supplemented by the energy harvested from vibrations of structures. Further research and implementation studies need to be carried out for this end.

D. Ring dual sensor variation of EMI technique

A new impedance measurement technique based on a dual PZT actuator sensor was developed using two separate but concentric PZT segments [51]. Because of the unique independent excitation and sensing mechanism for the segments, the dual PZT-EMI technique is shown to measure the structural responses, which are usually subdued in the conventional impedance techniques. The dual PZT impedance are shown to have the resonance peaks identical to those obtained by the conventional EMI method. The main advantage of the dual PZT technique is less vulnerability to temperature variations. The technique is particularly useful the structure being monitored is massive. This new variant technique requires further investigations for its implementation as the other conventional EMI technique.

VI. Concluding Remarks

In this paper, the fundamental concept of the Electro-Mechanical Impedance method (EMI), the technical requirements of the method and the numerous proof-of-the-concept tests for Structural Health Monitoring (SHM) applications are briefly discussed. The EMI method utilizes the impedance characteristics of the self-sensing piezoelectric ceramic actuator/sensors (PZT) for SHM. The recent technical developments in the areas of miniaturization of the testing equipment, the cost-effective adaptations of the technique, integration with wireless technologies and the energy harvesting methods have been discussed and the futuristic developments have been highlighted. The EMI method has a potential to develop into a unique SHM system.

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