Identification of structural damage severity and location using piezo-ceramic transducers

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IDENTIFICATION OF STRUCTURAL DAMAGE SEVERITY AND LOCATION USING PIEZO-CERAMIC TRANSDUCERS

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Identification of Structural Damage Severity and Location Using Piezo-Ceramic Transducers

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ABSTRACT

The use of smart piezoceramics, more commonly Lead Zirconate Titanate (PZT) patches, in structural health monitoring (SHM) has been of much research in recent years; especially in damage detection and structure identification using electro-mechanical impedance (EMI) technique which is based on the coupling relationships between the PZT and the host structure. In SHM, damage severity identification and localization are of great importance and are the main interests. PZT transducer has shown excellent sensitivity in structural damage identification and has been successfully applied in SHM. However, systematic investigation on damage propagation and localization is still in need.

In this study, monitoring of progressive damage using a single PZT transducer is investigated. Experiments are carried out by creating damages progressively along longitudinal and lateral axis on rectangular aluminum plates and extracting the admittance function through an impedance analyzer. The patterns of variations in signatures under different levels of damage are studied. In order to verify the experimental results, finite element analysis is also carried out and a recently developed 3D EMI model (Annamdas and Soh 2007) is adopted. A statistical index, the Root Mean Square Deviation (RMSD), is adopted to analyze both the experimental and numerical results quantitatively.

For the investigation on damage localization, multiple PZT transducers are used and both individual and parallel interrogation methods are applied. 9 PZT transducers are surface bonded to a rectangular aluminum plate and the RMSD values from all the PZT transducers are compared to locate the damages. Localization of a single damage is firstly presented to show the feasibility of the proposed method and subsequently monitoring of damage propagation direction is studied.

Conventionally, EMI monitoring system is connected using an extensive cable which is a serious limitation especially in the case of monitoring large scale

structures or where the structure is difficult to access. Therefore, wireless communication based SHM system is proposed to overcome the shortages of conventional method. A wireless communication based sensing system is developed and experiments are carried out to examine the reliability of the wireless system. The validation tests are carried out on an aluminum beam to monitor damage severity and location using two PZT transducers surface bonded to both ends of the beam. The signatures obtained using wireless sensing system are comparable to the ones obtained using a conventional impedance analyzer which shows the reliability of the wireless sensing system.

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CHAPTER 1 INTRODUCTION

1.1 Background

Structural components such as beams and columns are subjected to loadings, vibrations, wear and tear during their service life which may cause damages (Annamdas et al 2007). Once damage occurs, due to continuous usage of structure, the damage may develop to severe level and even lead to failure of the entire structure. Structural health monitoring (SHM) has emerged as an effective way in detection of structural damage occurrence to avoid catastrophic failure of structures. Therefore, research in SHM has become an area of interest for an increasing number of academics and laboratories.

Various approaches of SHM systems, especially the in-service and on-line health monitoring techniques have been developed in the past few decays (Giurgiutiu and Rogers 1998, Park et al 2001). These kinds of SHM techniques help to detect damages in the structures in the early stages thus reduce the cost of maintenance and repair. Smart material based techniques which is the use of smart materials like piezoceramic transducers for damage detection have become more and more popular. Lead Zirconate Titanat (PZT) is one of the most widely used smart materials for its capability of both actuation and sensing. Many researchers have devoted themselves into study of theoretical modeling and practical applications of PZT transducers in SHM.

1.1.1 PZT transducers

PZT transducers show a marked piezoelectric effect among its other ferroelectric properties—that is, it develops a voltage difference across two of its faces when

deformed (used for sensor applications), and physically strained when applied external an electric field (used as actuators). It is ferroelectric, in other words, it has a spontaneous polarization which can be reversed in the presence of an electric field. PZT transducer is used to make ultrasound transducers and other sensors and actuators, as well as high-value ceramic capacitors and Ferroelectric RAM chips. Special type, known as peizoceramics which is one of the type of $\text{Pb}[\text{ZrxTi1-x}]\text{O3}$ is also used in the manufacture of ceramic resonators for reference timing in electronic circuitry. In the form of a small sized patch wafer, PZT transducers are usually bonded to the surface, or embedded within the structural substrate. Extremely light and non-invasive, the PZT transducer does not significantly impede the mechanical functions of its host structure (Giurgiutiu and Zagrai, 2000). Because of all these preeminent features the application of PZT transducer for SHM definitely deserves further investigation.

1.1.2 SHM by electromechanical impedance (EMI) technique

The EMI method has emerged as a widely recognized technique for dynamic identification and health monitoring of structural systems. Even though the piezo-electric crystals (PZT transducers) were first employed in 1940 (Banks et al., 1996b), their application in the EMI method is one of recent (decade long) developments. The capabilities of the EMI method and its advantages have been experimentally acknowledged by many researchers (Sun et al, 1995; Ayres et al, 1998; Guirgiutiu *et al.*, 1999; Park *et al.* 1999, 2000a, b, 2001; Soh *et al.*, 2000; Bhalla, 2001, Yun and Park 2008). In this method, a PZT transducer needs to be permanently bonded on the surface of the monitored structure. The self sensing of PZT transducer enables transduction of electric energy to mechanical energy and vice versa between the PZT transducer and the host structure (Liang et al., 1994) producing structural response known as electromechanical (EM) admittance. Thus, in this method, PZT transducer behaves both as active actuator and active sensor.

The EM admittance response of the smart system is derived from the dynamic interaction relation between the PZT transducer and the host structure. The EMI method has been proven to be direct and easy to implement. In damage identification, it is based on the principle of comparing the healthy state signatures with the post damage signatures, similar to the conventional vibration methods. The self-sensing feature of a PZT transducer enables transduction of electrical energy to mechanical energy, and vice-versa, between the PZT transducer and the host structure. The electrical admittance of the PZT transducer can be expressed as a coupling of mechanical impedance of the actuator and the drive-point mechanical impedance of the host structure (Liang et al., 1994). When damage occurs, certain parameters such as mass, stiffness and damping are altered thus the structural impedance is altered. Changes in the signature will be a reliable indicator of damage presence.

Over the past few years, several EMI models have been developed by researchers. The first EMI model for PZT-structure interacting system is the 1-D model proposed by Liang et al. (1994). Zhou et al. (1995) extended the 1-D impedance model to a generic two dimensional (2D) model which models the coupling of a 2D PZT transducer element to the host structure, in which the structural impedances are represented by direct impedances and cross impedances. Bhalla and Soh (2004a) identified several limitations to the 1D model and 2D model of Zhou et al. (1995) and introduced a concept of “effective impedance” to formulate the EM admittance. Yang et al (2005) also developed a generic 2D EMI model. Most recently, Annamdas and Soh (2007) developed the 3 –D EMI model which has been adopted in the numerical investigations of this study. Further discussion will be presented in later chapters.

1.1.3 EMI based damage identification

Damage detection is an important aspect in the field of EMI based SHM techniques. In damage identification analysis, the EMI method has been proved to be very effective in detecting the presence of incipient damages. Many researchers have carried out experimental based investigations to study damage identification capabilities of PZT transducer based EMI techniques (Sun *et al.* (1995), Park *et al.* (2000a), Soh *et al.* (2000)) and have demonstrated the reliability of this technique. Naidu (2004) has established that a single PZT transducer is sensitive enough to indicate damage propagation in a one-dimensional (1-D) beam structure. However, these experimental studies were not verified by any EMI model. Relationships between the patterns of changes in the EM impedance signatures to physical changes in the structure are very important in precise damage location identification and meaningful damage characterization of different types of damages. Winston *et al.* (2001) showed that the FE model could predict the natural frequencies and mode shapes for a free-free beam up to 100 kHz, very close to those obtained for a PZT transducer driven structure. Giurgiutiu and Rogers (1999) and Giurgiutiu and Zagrai (2000) have also established that the real parts of EM impedance and admittance signatures are direct representatives of structural response. Thus, FE models and other analytical models can be used to examine the nature of signature changes.

In EMI based damage identification technique, quantification of acquired EM impedance signatures is very helpful to understand the character of structural damages. To analyze the structural damage quantitatively, there are several statistical method for signature comparison such as, Root Mean Square Deviation (RMSD) technique, Signature Assurance Criteria Technique (SAC), and Mean Absolute Percentage Deviation (MAPD). Hey *et al* (2006) has established that RMSD is a good statistical analysis index in identifying damage location. Therefore, in the present study, RMSD index will be used for statistical analysis.

1.1.4 Application of wireless communication based SHM

Wireless sensors have been proposed for use in structural health monitoring systems because they offer low-installation costs and automated data processing functionality. Strong interest in applying wireless sensing technologies within structural health monitoring systems has grown in recent years (Park et al 2009, Cho et al 2008, Lu et al 2005). Subramaniam et al. (1997) has presented a wireless health monitoring for the fabrication of Micro-Electromechanical System (MEMS) accelerometers, which have interdigital transducers (IDTs) attached on a PZT transducer substrate. The application of these sensors to health monitoring technology has been discussed by Varadan and Varadan (1999) and Varadan (2002). Wireless sensing technology and system frameworks have also been presented by Pines and Lovell (1998). The use of wireless communication for SHM data acquisition was illustrated by Straser and Kiremidjian (1998). Lynch et al. (2003a, b) extended the work by embedding damage identification algorithm into wireless sensing unit. With the rapid advancement of sensing, microprocessor, wireless technologies, it is possible to assess the benefits from the application of wireless communication technologies in the field of structural health monitoring.

1.2 Motivation

Monitoring of damage severity and damage localizations have always been two very important aspects of EMI based SHM. The reliability of PZT transducer on damage detection has been studied by many researchers and PZT transducer has shown great sensitivity to structural damages. However, most of the research focuses on single damage detection. Little work has been reported on monitoring of damage propagation even on 1D beam structures. This study aims to investigate monitoring of damage severity and locations on plate structures. Multiple damage localization on plate structure is also studied using PZT transducer array surfaced

bonded to the structure.

Additionally, as the conventional impedance analyzer is limited due to the wire connection which is not practical in real life application, wireless technology has been more and more popular in SHM and attracted many researchers. Different types of wireless sensing systems have been developed in the past few decades. However, research on wireless sensing using PZT transducers is still necessary to achieve higher accuracy in data acquisition. Development of wireless sensing system enables the EMI based SHM to be more widely applied in practice.

1.3 Objectives of Research

The main objective of this research is to systematically study monitoring of structural damages, single and multiple, using PZT transducers. Efforts are concentrated on identifying the severity and locations of single and progressive damages using a single PZT transducer and multiple PZT transducers with individual and parallel interrogation methods. Finite Element Modeling adopting 3D EMI model is carried out for verification of the experimental investigation.

Additionally, wireless communication between the PZT transducers and the analyzer is developed using transmitters and receivers. This enables a wireless communication based SHM which is very helpful in monitoring large scaled structures where difficulties exist in accessibility.

In this research, structural damage characters in terms of severity, location and propagating direction is studied. Finite element modeling is performed for

verification of experimental investigation. Overall, the main targets of this study are summarized as following:

1. Experimental and numerical study on damage propagation using single PZT transducer
2. Experimental and numerical study on single damage localization using PZT transducer array
3. Experimental and numerical study on monitoring of multiple damage propagation and locations using PZT transducer array
4. Development of wireless communication between PZT transducers and analyzer

1.4 Organization of Thesis

This thesis comprises a total of seven chapters, including this chapter on Introduction.

Chapter 2 reviews the definition and concept of structural health monitoring, smart materials and smart systems, and EMI based SHM techniques. The properties of the piezoelectric material including piezoelectric constitutive relations are particularly discussed in this chapter. EMI-type model for PZT-Structure interacting system is also covered. Investigations on damage identification by researchers in the past decade are studied. Finally, the available wireless sensors and SHM systems are compared and studied.

Chapter 3 presents experimental investigation on monitoring of damage propagation using single PZT transducer on non-symmetrical aluminum plates. Experimental

results are analyzed qualitatively and quantitatively. Finite element modeling is performed to verify the experimental results.

Chapter 4 presents studies on damage localization using multiple PZT transducers on an aluminum plate. Individual and parallel interrogation methods are used for data acquisition. RMSD index is used to quantify deviation of damaged stage signatures to locate damages. Numerical modeling for individual interrogation is also presented as verification of experimental results.

Chapter 5 presents studies on monitoring of damage severity and localization using multiple PZT transducers. Correlations between RMSD changes and damage locations are investigated, and both individual and parallel interrogation methods are used.

Chapter 6 presents a newly developed PZT transducer based wireless sensing system. Validation tests are carried out on an aluminum beam structure for monitoring of damage propagation. Results obtained from wireless sensing system are compared to results from conventional sensing system to examine its accuracy.

Finally, Chapter 7 summarizes the work that has been accomplished at present and lists the future work.

CHAPTER 2 LITERATURE REVIEW

2.1 An Overview On SHM

SHM is a cluster of integrated research activities, consisting of engineering, social and economical investigations which was initiated and continuously expanded over the past decades. It is defined in the literature as the “acquisition, validation and analysis of technical data to facilitate life cycle management decisions,” SHM denotes a reliable system with the ability to detect and interpret adverse ‘changes’ in a structure due to continuous operation or damages (Kessler et al., 2002). With the acquired knowledge of the integrity of the in-service structure on a continuous real-time base using SHM techniques, the end users can determine with more confidence about the optimum use of the structure and avoid catastrophic failures. Besides, the manufacturers can also improve their products, reduce inventory and minimize the cost.

With the advancement in smart material technology, there has been a significant increase in interest in developing new diagnostic system for monitoring the integrity of and the detection of damage in both existing and new structures. Additionally, the minimization of human involvement in this monitoring process will reduce human errors, and save time and labour involved in the process. Therefore, an ideal SHM technique involves the development of an autonomous system to continuously monitor and detect damages.

There are various approaches for health monitoring and damage detection. Non-destructive evaluation (NDE) based SHM has emerged as pioneering field during the last two decades. In general, the SHM-NDE methodologies can be classified, based on their basic principle, as

- a) Visual inspection method,
- b) Low frequency vibration techniques,
- c) Static response based techniques,
- d) Localized NDE techniques,
- e) Smart system based techniques.

2.1.1 Visual inspection method

Visual inspection method is one of the most commonly employed NDE techniques in the industry which is carried out by trained personnel for the assessment of structural integrity of structures. The techniques involved are either by visual checks for cracks and damages, using tapping test with boning rod, magnetic particles or dye-penetration, or a combination of the above (Bhalla, 2004). Visual inspection is a common method of quality control, data acquisition and data analysis and this method also serves as the standard by which all other nondestructive evaluation technologies may be compared.

However in this method, checks on the structure must be carried out periodically which is time consuming and costly. The reliability of the assessments may not be consistent since it depends highly on the experience of the inspector. Moreover, visual inspections are very tedious and laborious (Kessler et al., 2002). Parts of the structures to be inspected may be hard to reach or are located at the external of structures, rendering the inspection difficult to carry out and may pose safety hazards to the inspector. Some times, it needs dismantling of the critical components before inspections and reassembling afterwards (Boller, 2002) or it needs removing covering finishes to assess the civil-structure members. Most of the existing visual inspection techniques demand holding the use of a part or whole of structure till the probe is done, which proves impractical for the large-sized civil structures (Rens et al. 1997). All of the above points results in visual inspection

being time consuming, laborious and costly. Thus the need is there for a new SHM system to reduce time, efforts and costs, and to enable monitoring structures while in service throughout their design lives.

2.1.2 Low frequency vibration techniques

In the field of SHM, vibration-based technique is one of the general approaches to detect and quantify damage to a structural system (Ryue and White, 2007). These techniques are based primarily on the structural dynamic theory. In principle, changes occur in the structural parameters, namely the stiffness matrix and the damping matrix when damage occurs. Particularly, structural stiffness, EI , decreases in the presence of damages, thereby reducing the natural frequencies. This has led to many damage detection methods using modal analysis. The structure in question is excited by low frequency actuation (usually less than 100Hz), either harmonic or impulse. The resulting vibration responses like displacements, velocities and accelerations are measured at locations of interest in the structure. Then, damages are identified following the concept that damage to structure changes the modal parameters of the structure. The mode shapes and natural frequencies corresponding to these mode shapes are extracted and a set of suitable modal parameters can be identified, thereby yielding information pertaining to the locations and severity of the damages (Salawu, 1997; Doebling et al., 1998; Zou et al., 2000; Giurgiutiu and Zagrai, 2002). Researchers proposed many low frequency vibration based SHM methods like the change in curvature mode shapes (Pandey et al., 1991), the change in stiffness (Zimmerman and Kaouk, 1994) and the change in flexibility (Pandey and Biswas, 1994). Many other related publications can be found (Betti and Testa, 1995), reporting the use of similar algorithms, based on the basic principle to identify changes in the modal and the structural parameters (or their derivatives) resulting from damages.

The monitoring of structures involving only the first few low frequency modes of vibration are essentially based on the low frequency dynamic response. Therefore, only a limited number of modal frequencies and the corresponding mode shape vectors can be extracted. Thus, certain damages remain unnoticed as stiffness change has different sensitivity to each modal vector and it may not significantly affect some of the mode shapes. Effective damage detection is not possible as at low frequency, small cracks or incipient damages cannot significantly affect the global modal parameters (Pandey and Biswas, 1994). Therefore, the low frequency techniques are not discernible for the detection of relatively small sized cracks. In addition, the procedure is very time consuming and inaccurate signature could be obtained as there is likelihood to be contaminated with measurement noise associated with the ambient vibrations (Doebling et al., 1998), typically less than 100Hz (which also happen to be in the low frequency range). Reliability and health assessment of these global methods also requires accurate modeling of the damaged structure and a conservative choice of the limit capacity of the structure.

2.1.3 Static response based techniques

Static response based technique was formulated by Banan and Hjelmstad (1994) based on static displacement response of structures. These methods include the static displacement response technique (Banan et al., 1994) and the static strain measurement technique (Sanayei and Saletnik, 1996). A selected number of forces and the corresponding displacements were measured, and a set of member constitutive properties or structural parameters were then derived. Any change in the parameters from the baseline healthy state is an indicator of damage.

Difficulty in practical implementation is the major draw back of this technique. There are difficulties in establishing a frame of reference for the measurement of large scale structures (Bhalla, 2004). For contact measurement, it would demand the

construction of a secondary structure on an independent foundation (Banan et al., 1994; Sanayei and Saletnik, 1996). In addition, the application of large loads to cause measurable deflections (or strains) needs huge machinery and power input making assessment tedious (Bhalla, 2001, 2004).

Sanayei and Saletnik (1996) proposed another similar technique based on static strain measurements. The advantage of this technique over the displacement approach is that strain measurements can be made with a higher degree of precision and can be applied without practical limitations as compared to the displacement measurements. However, application on real-life structure remains as tedious.

2.1.4 Localized NDE techniques

Localized NDE techniques rely on localized interrogation of the structures. Some of the available methods are: ultrasonic wave propagation technique, acoustic or ultrasound emission, eddy-currents, magnetic field analysis, impact echo testing, thermal field and X-ray analysis (Doherty, 1987).

The main limitation of such methods is that a portion or whole of the structure is rendered unavailable during the inspection period (Doebling et al., 1998). Some of the other drawbacks are that only surface cracks can be detected, and dependency on the known vicinity of the fracture damage and knowledge of the approximate location of the damage a priori is required.

In general, most of these local methods are quite impractical for comprehensive monitoring of large structures with complex geometry. However, reasonably good results can be obtained for assessing the condition of portions of a structure or individual members.

2.1.5 Smart system based techniques

Smart materials are those which have the ability to change their physical properties, such as stiffness, damping, viscosity and shape, in a specific manner in accordance to the type of stimulus they have to respond (Rogers et al., 1988). The scientific community has acknowledged the underlying properties of smart materials for many years, but adapting these materials into smart systems is a recent development. Examples of smart materials include materials such as optic fibre, shape memory alloy (SMA), electric-rheological (ER) and piezoelectric material, which is employed in the present study.

Smart systems are also referred to as adaptive material systems or intelligent material systems. The concept of smart system according to Ahmad (1988) is a system that is capable of recognizing an external stimulus and responding to it within a given time in a predetermined manner (Ahmad et al., 1988). In addition, it has the capability of identifying its status and may optimally adapt its function to external stimulus or may give appropriate signal to the user.

A smart system incorporates the following component features, by definition:

- i. **Sensor:** The sensors are either embedded within a structure or surface-bonded to the structure. The function of the sensor is to measure the intensity of the stimulus associated with a stress, strain, electrical, thermal or a chemical phenomenon, or its associated effect on the structure such as damages, cracks etc.
- ii. **Actuators:** Similar to sensors, the actuators are also either embedded within or surface-bonded on to the surface of structures. The actuators possess a property of undergoing change in their geometrical configuration, stiffness or energy dissipation properties in a controlled manner on being excited by an external stimulus.

- iii. Control mechanism: The mechanism integrates and controls the action of the sensors and actuators. It typically involves data processors, data transmission and interpretation links, and control software.

In smart system based techniques, unlike the low vibration techniques, the host structures are not subjected to global excitations. Smart materials are surface bonded or embedded in the host structures and are subjected to high frequency excitation. Among the different types of smart materials, transducer made of piezoceramic (PZT) material (Park, 2000), are one of the most widely used material in this technique. PZT transducer works on the principle of EMI technique. The governing principle is that the PZT transducer actuates harmonically in the presence of electric field to produce a structural response which is known as ‘admittance signature’. The admittance signature is a function of the stiffness, mass and damping of the host structure (Sun et al. 1995), and the length, width, thickness and orientation of the PZT transducer (Wetherhold et al. 2003). The changes in the admittance signature are indicative of the presence of structural damages.

Smart material based SHM techniques have been extensively used nowadays and have attracted many researchers studying and developing this technique. The advantages of employing PZT transducer in SHM are as follows;

1. It allows the early detection of damages as it uses a high frequency of excitation. Thus the wavelength generated is very small and can sense small cracks.
2. It has the ability to localize and characterize damages owing to the use of high frequency.
3. The inherent properties of PZT allow them to be employed as transducers thereby eliminating the need for additional equipments.

4. PZT transducers are small and non-intrusive. Installation can commence upon construction of the structure.
5. Monitoring of structure can be done remotely and do not require the exclusive access to the structure.

2.2 Piezoceramic Transducers

2.2.1 History of piezoceramic transducers

Piezoelectric materials are materials that exhibit piezoelectric properties. This extraordinary property has the ability to experience a dimensional change when being applied with a potential difference across a certain direction. The converse is also true such that an electric potential is developed across their boundaries when subjected to a mechanical stress. They have been successfully implemented in many applications as distributed vibration sensors (Choi and Chang., 1996; Kawicki, 1998), strain sensors (Sirohi and Chopra, 2000a), actuators (Sirohi and Chopra, 2000b), and pressure transducers (Zhu, 2003).

The first piezoelectric material was discovered in 1880 by Pierre and Jacques Curie during their study of the effects of pressure on the generation of electrical charge by crystals such as Quartz, tourmaline, and Rochelle salt. These crystals are known as piezoelectric crystals. In the 1940s and 1950s, the development of polarized piezoelectric ceramics, like barium titanate and lead zirconate titanate (PZT) brought about commercialization of piezoelectric materials. In 1958, the terminology, linear piezoelectric formulations and the methods to measure their elastic and electric properties were standardized (Bechmann and Fair, 1958). Later on, new types of piezoelectric materials were developed based on both ceramics and polymers. Now, these are available in different forms, such as film (Han, *et al.*,

1997; Lee *et al.*, 2000), paint, powder, single fibre and multilayered. Soon, another class of piezoelectric material, known as piezoelectric polymers is developed.

Nowadays, there are two widely used piezoelectric materials:

1. Piezoceramics, like lead zirconate titanate (PZT)
2. Piezopolymers, like polyvinylidene fluoride (PVDF)

2.2.2 Properties of piezoceramic materials

Piezoelectric materials produce a voltage in response to an applied force, usually a uniaxial compressive force. Similarly, a change in dimensions can be induced by the application of a voltage to a piezoelectric material. In this way they are very similar to electro-strictive materials. There are various materials like macro fiber composite actuators and active fiber composite actuators, however, the most widely used ceramics are PZT, with composition $\text{Pb}(\text{Zr}_{1-x}\text{Ti}_x)\text{O}_3$. They are brittle materials and are manufactured as small shaped parts, with relatively small surface area. Most commercially available piezoceramics possess perovskite structure as shown in Figure 2.1. This simple octahedral arrangement consists of 8 corner sharing oxygen octahedral forming a cube, a small cation (Ti, Zr) occupying its center and larger cations (Pb, Ba) filling the interstices between octahedral. The perovskite structure exists in two crystallographic forms. Below the Curie temperature they have a tetragonal structure and above the Curie temperature they transform into a cubic structure. In the tetragonal state, each unit cell has an electric dipole, i.e. there is a small charge differential between each end of the unit cell. A mechanical deformation (such as a compressive force) can decrease the separation between the cations and anions which produces an internal field or voltage.

Figure 2.1: Crystal structure of a traditional piezoelectric ceramic
 (a) Tetragonal perovskite structure below the Curie temperature
 (b) Cubic structure above the Curie temperature.

Mixing, binding, sintering and poling are the processes involved in manufacturing the ceramic transducers. The process of converting a crystal material into piezoelectric material permanently is called poling which is the application of an intense electric field ($>2000\text{V/mm}$) to the piezoceramic. Piezoelectric materials ought to be heated above their Curie temperature for an effective poling. With the application of intense electric field, all dipoles are aligned along the poling axis (see Figure 2.2). When the field is removed, the electric dipoles stay roughly, but not completely, in alignment. The material now has a remnant polarization which can be degraded or even completely eliminated by exceeding the mechanical, thermal and electrical limits of the material. Cooling below Curie temperature is compulsory before removal of field to ensure a permanent alignment of dipoles. Upon poling, the material is in an asymmetric form and thus possesses piezoelectric properties. However, excessive temperature, electric field and mechanical loading must be avoided to prevent degradation and loss of serviceability.

Figure 2.2: Electric dipoles in domains
(a) unpoled ferroelectric ceramic, (b) during and (c) after poling

It is reported in the literature that the properties of piezoceramics transducers vary due to inhomogeneous chemical composition, mechanical differences during formation and the polarization process (Sensor Technology Ltd., 1995) and statistical variations are reported to be very common (Giurgiutia and Zagari, 2000).

2.2.3 Working principle of piezoceramic transducers

The direct and converse effects of piezoelectric phenomena, involving cross coupling interaction between mechanical and electrical behavior of PZT transducer, can be modeled by linear constitutive equations involving two mechanical variables and two electrical variables.

The basic constitutive relations for piezoelectric materials, under small field condition can be written as (IEEE standard, 1987)

$$D_i = \overline{\varepsilon}_{ij}^T E_j + d_{im}^d T_m \quad (\text{Direct Effect}) \quad (2.1)$$

$$S_k = d_{jk}^c E_j + \overline{s}_{km}^E T_m \quad (\text{Converse Effect}) \quad (2.2)$$

In direct effect, when a mechanical stress is applied across the PZT transducer, as shown in Figure 2.2, Eq. (2.1) is used for measuring the electrical charge generated. In converse effect, when electric field is applied across the PZT transducer as shown in Figure 2.2, Eq. (2.2) is used for deriving the induced mechanical strain.

The direct effect is used in sensor applications, where as the converse effect is used in actuator applications. Combinations of both equations are used in all high frequency excitation where most of the time the PZT transducer is used both as an actuator and a sensor. More generally, Eq. (2.1) and (2.2) can be rewritten in the matrix form as (Sirohi and Chopra, 2000)

$$\begin{bmatrix} D \\ S \end{bmatrix} = \begin{bmatrix} \overline{\varepsilon^T} & d_{im}^d \\ d_{jk}^c & \overline{s^E} \end{bmatrix} \begin{bmatrix} E \\ T \end{bmatrix} \quad (2.3)$$

where $[D]$ (Coulomb/m²) is the electric displacement vector of size (3 x 1), $[S]$ 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/m²) the stress tensor of size (6 x 1). $[\overline{\varepsilon^T}]$ (F/m) is the dielectric permittivity tensor of size (3 x 3) under constant stress, $[d_{im}^d]$ (C/N) and $[d_{jk}^c]$ (m/V) are the piezoelectric strain coefficient tensors of sizes (3 x 6) and (6 x 3) respectively, and $[\overline{s^E}]$ (m²/N) is the 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 parameter that has been measured at constant stress and electric field respectively. A bar above some parameters indicates that these parameters are measured at dynamic conditions (hence complex in nature). In the absence of mechanical stress, strain per unit electric field is defined as the piezoelectric strain coefficient d_{jk}^c (see Eq. (2.2)). Similarly, in the absence of an electric field, the electric displacement per unit stress is given by d_{im}^d (see Eq. (2.1)). The two coefficients are numerically equal. In both d_{jk}^c and d_{im}^d , the first subscript denotes the direction of the electric field and the second subscript denotes the direction of the associated mechanical strain

Figure 2.3: PZT transducer under electric field and mechanical stress

For a sheet of piezoelectric material (Figure 2.3), the poling direction is usually along the thickness (axis 3). The matrix $[d_{jk}^c]$ depends on the crystal structure. For PZT transducer, as reported in the literature, it is given by

$$[d_{jk}^c] = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (2.4)$$

$$d^d = (d^c)^T \quad (2.5)$$

The coefficients d_{31} , d_{32} and d_{33} are numerically equal to the normal strains in the directions 1, 2 and 3 respectively due to a unit electric field applied along the poling direction 3 under stress free boundary conditions. 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 . It is not possible to produce shear in the 1-2 plane purely by the application of an electric field. Similarly, shear stress in the 1-2 directional plane does not generate any electric

response. In all poled piezoelectric materials, d_{31} is negative and d_{33} is positive. For a good sensor, the algebraic sum of d_{31} and d_{33} should be the maximum and at the same time, ϵ_{33} and the mechanical loss factor should be minimum (Kumar, 1991; Bhalla, 2004).

The compliance matrix has the form

$$\overline{s}^E = \begin{bmatrix} \overline{s}_{11}^E & \overline{s}_{12}^E & \overline{s}_{13}^E & 0 & 0 & 0 \\ \overline{s}_{21}^E & \overline{s}_{22}^E & \overline{s}_{23}^E & 0 & 0 & 0 \\ \overline{s}_{31}^E & \overline{s}_{32}^E & \overline{s}_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & \overline{s}_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & \overline{s}_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & \overline{s}_{66}^E \end{bmatrix} \quad (2.6)$$

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

$$\overline{s}_{11}^E = \overline{s}_{22}^E = \overline{s}_{33}^E = \frac{1}{\overline{Y}^E} \quad (2.7)$$

$$\overline{s}_{12}^E = \overline{s}_{13}^E = \overline{s}_{21}^E = \overline{s}_{31}^E = \frac{-\nu}{\overline{Y}^E} \quad (2.8)$$

$$\overline{s}_{44}^E = \overline{s}_{55}^E = \overline{s}_{66}^E = \frac{1}{\overline{G}^E} \quad (2.9)$$

where $\overline{Y}^E$ is the complex Young's modulus of elasticity, $\overline{G}^E$ the complex shear modulus, and ν the Poisson's ratio. It may be noted that both $\overline{Y}^E$ and $\overline{G}^E$ are related as

$$\overline{G}^E = \frac{\overline{Y}^E}{2(1+\nu)} \quad (2.10)$$

And the permittivity matrix is:

$$[\overline{\varepsilon}^T] = \begin{bmatrix} \overline{\varepsilon}_{11}^T & 0 & 0 \\ 0 & \overline{\varepsilon}_{22}^T & 0 \\ 0 & 0 & \overline{\varepsilon}_{33}^T \end{bmatrix} \quad (2.11)$$

The stress vector is written as

$$T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} = \begin{bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{23} \\ T_{31} \\ T_{12} \end{bmatrix} \quad (2.12)$$

The strain vector can be written in the form:

$$S = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} S_{11} \\ S_{22} \\ S_{33} \\ S_{23} \\ S_{31} \\ S_{12} \end{bmatrix} \quad (2.13)$$

The electric displacement vector can be written as:

$$D = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} D_{11} \\ D_{22} \\ D_{33} \end{bmatrix} \quad (2.14)$$

And, the electric field vector is:

$$E = \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} E_{11} \\ E_{22} \\ E_{33} \end{bmatrix} \quad (2.15)$$

Eq. (2.1) is commonly termed as the actuator equation, and Eq. (2.2) is termed as the sensor equation. Actuator applications are based on the converse piezoelectric effect, and for sensor applications, the direct piezoelectric effect. Therefore, when the transducer is bonded to a structure and subjected to an electric field, an induced strain field occurs. Conversely, when the transducer is exposed to a stress field, an

electric charge is generated in response. Such is the uniqueness of the piezoceramic material, which enables the material to perform both as an actuator and a sensor.

2.3 Electromechanical Impedance (EMI) Method

The electromechanical impedance (EMI) method is one of the recent developments in the field of smart system based structural health monitoring. The basic feature of the EMI method is the use of smart piezoelectric (PZT) materials as both sensors and actuators. One of the most important advantages of EMI method is that, PZT transducer can excite the structure at high frequencies, typically 10 – 500 kHz, thus activating the higher modes of the structure. These higher modes are able to capture the local changes of the structure, where the conventional vibration methods fail. Further more, the small size, lightweight and self-sensing features of the PZT transducer makes it non-intrusive to the structure and reduces the system components significantly. The capabilities of the EMI method and its advantages have been experimentally acknowledged by many researchers (Sun et al, 1995; Ayres et al, 1998; Guirgiutiu *et al.*, 1999; Park *et al.* 1999, 2000a, b, 2001; Soh *et al.*, 2000; Bhalla, 2001).

The EMI method is based on the same principle of comparing healthy state signatures with the post damage signatures, similar to the conventional vibration methods. The self-sensing feature of a PZT transducer enables transduction of electrical energy to mechanical energy, and vice-versa, between the PZT transducer and the host structure. The electrical admittance of the PZT transducer can be expressed as a coupling of mechanical impedance of the actuator and the drive-point mechanical impedance of the host structure (Liang et al., 1994). Mechanical impedance of host structure is dependent on its mass, stiffness and damping properties. Damage in a structure alters the stiffness, damping and mass, by which

mechanical impedance is altered. When a PZT transducer is bonded on the structure and actuated, the damage-induced change in the mechanical impedance of the structure is reflected in the electrical admittance of the PZT transducer. When a structure is monitored at a later point of time by extracting the PZT transducer's admittance response to exciting frequency, which is also called the admittance signature, the changes in the signature becomes indicative of the presence of structural damage (Sun et al, 1995). Thus, it is important for any numerical or analytical model to properly predict and describe the admittance signature using the actuations of PZT transducer for its successful implementation.

Over the past few years, the EMI technique was widely researched and several other models were developed. Zhou et al. (1995) extended the 1-D impedance model to a generic two dimensional (2D) model which models the coupling of a 2D PZT element to the host structure, in which the structural impedances are represented by direct impedances and cross impedances. Bhalla and Soh (2004a) identified several limitations to the 1D model and 2D model of Zhou et al. (1995). In the 1D model, all members are assumed to be 1D and PZT has negligible stiffness, the 2D PZT actuation was ignored. In the 2D model, the difficulties lie in the direct applications. The direct and cross impedances (which amounts to 4 complex unknowns) have to be solved first before complete information about the structure can be acquired. Thus, Bhalla and Soh (2004a) have introduced a concept of "effective impedance" and formulated the electromechanical admittance based on this effective impedance. A detailed review of the EMI models is presented in the following sections.

2.3.1 1-D EMI Models

The first EMI-based model for PZT-structure interacting system was proposed by Liang et al. (1994), as shown in Figure 2.4. In this model the host structure was assumed to be a mass-spring-damper system undergoing horizontal vibration, and

the PZT transducer a thin bar fixed on one end and connected to the host structure on the other end. The mechanical aspect of the PZT transducer is described by its short-circuit mechanical impedance, Z_p . The host structure is generalized by its driven point mechanical impedance, Z_{str} , which includes the effect of mass, stiffness, damping, and boundary conditions. The PZT transducer is powered by voltage, $\bar{V}$ or current, $\bar{I}$. The entire system can be electrically represented by an EM admittance of the PZT transducer. The length, width and thickness of the PZT transducer are l , w and h , respectively.

Figure 2.4: 1-D model of electromechanical interaction of a PZT transducer with the host structure

The expression for the EM admittance (the inverse of EMI) is

$$\bar{Y} = 2\omega j \frac{wl}{h} \left[(\bar{\epsilon}_{33}^T - d_{31}^2 \bar{Y}^E) + \left(\frac{Z_a}{Z + Z_a} \right) d_{31}^2 \bar{Y}^E \left(\frac{\tan \kappa l}{\kappa l} \right) \right] \quad (2.16)$$

However, the major limitations of the 1D model are that, this model is applicable only for thin PZT transducers and the direction of vibration is restricted to 1D, i.e. along the length of the PZT transducer (Annamdas 2007).

2.3.2 2-D EMI Models

Zhou et al. (1995, 1996) extended the 1D impedance method of Liang (1994) to model the interactions of a generic 2D PZT element coupled to a 2D host structure. The analytical model of these researchers is schematically shown in Figure 2.5.

Figure 2.5: Modelling of 2D physical coupling by impedance approach(Bhalla, 2004)

Zhou et al. (1995) derived the following expression for the EM admittance across the PZT terminals

$$\bar{Y} = G + Bj = j\omega \frac{wl}{h} \left[\frac{\bar{\epsilon}_{33}^T}{(1-\nu)} - \frac{2d_{31}^2 \bar{Y}^E}{(1-\nu)} + \frac{d_{31}^2 \bar{Y}^E}{(1-\nu)} \left\{ \frac{\sin \kappa l}{l} \quad \frac{\sin \kappa w}{w} \right\} N^{-1} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \right] \quad (2.17)$$

Bhalla and Soh (2004a) introduced a new definition of mechanical impedance based on ‘effective velocity’ rather than ‘drive point velocity’. Considering a finite sized square PZT transducer, surface bonded to an unknown host structure (as shown in Figure 2.6), subjected to a spatially uniform electric field undergoing harmonic variation with time. The transducer has half-length equal to ‘l’. Its interaction with the structure is represented in the form of boundary traction ‘f’ per unit length, varying harmonically with time.

Figure 2.6: Modelling of interaction of PZT transducer and structure in 2D(Bhalla, 2004)

The complex electro-mechanical admittance of the PZT transducer is given by

$$\bar{Y} = \frac{\bar{I}}{\bar{V}} = G + Bj = 4\omega j \frac{l^2}{h} \left[\frac{\bar{\epsilon}_{33}^T}{(1-\nu)} - \frac{2d_{31}^2 \bar{Y}^E}{(1-\nu)} + \frac{2d_{31}^2 \bar{Y}^E Z_{a,eff}}{(1-\nu)(Z_{s,eff} + Z_{a,eff})} \left(\frac{\tan \kappa l}{\kappa l} \right) \right] \quad (2.18)$$

which is the desired coupling equation for a square PZT transducer. It should be noted that a factor of 4 is introduced in the final expression, since ‘l’ here represents half-length of the transducer. However, the limitations of this approach are that the vibrations in the thickness direction are ignored and it is only applicable to PZT transducers (Annamdas 2007).

2.3.3 3-D EMI Models

A new ‘Directional Sum Impedance’ (DSI) model which is based on 3D interaction of PZT-host structure was developed by Annamdas and Soh (2007). This new model considers the extensional actuations along both the length and width directions and the longitudinal actuations along thickness of the transducer. This model is applicable for both the surface bonded and the embedded PZT transducer types. Thus, DSI model contains additional features over the existing PZT-host structure interaction models. Figure 2.7 illustrates the PZT-host structure interaction model using embedded and surface bonded PZT transducers. Figure 2.7 (a) depicts the embedded PZT transducer interaction with the host structure in the X, Y and Z

directions along the length ($2W$), width ($2L$) and thickness ($2H$) of the PZT transducer.

Figure 2.7: 3D distribution of forces and impedances on one-quarter of PZT transducer

(a) Embedded PZT transducer (b) Surface bonded PZT transducer.

3D EM admittance is the ratio of the resultant electric current to the applied electrical voltage

$$\overline{Y}_A = \frac{I}{V} \quad (2.19)$$

where V is the applied voltage across the PZT transducer.

The final complex 3D EM admittance of the PZT transducer is given as

$$\overline{Y}_C = G + Bj = \frac{j\omega LW}{2H} \left[\overline{\varepsilon}_{33} + Y_R \left\{ d_{31}\lambda_1 \left\{ [A_0 \sin kL - d_{31}] + R[C_0 \sin kW - d_{32}] + R[E_0 k \cos k2H - d_{33}] \right\} + \right. \right. \quad (2.20)$$

$$\left. \left. d_{32}\lambda_2 \left\{ R[A_0 \sin kL - d_{31}] + [C_0 \sin kW - d_{32}] + R[E_0 k \cos k2H - d_{33}] \right\} + \right. \right.$$

$$\left. \left. d_{31}\lambda_3 \left\{ R[A_0 \sin kL - d_{31}] + R[C_0 \sin kW - d_{32}] + [E_0 k \cos k2H - d_{33}] \right\} \right\} \right]$$

In this case, the PZT transducers and the specimens are symmetrical along the XY plane; hence, only one-quarter of the transducer and specimen are considered. The

3D EM admittance $\overline{Y}_C$ of the complete specimen is therefore given as

$$\overline{Y}_C = 4\overline{Y}_A \quad (2.21)$$

2.4 Damage Identification Using Piezoceramic Transducers

As mentioned in Chapter 1, monitoring of structural damage is an important aspect of SHM. In this section, a review on investigations on damage monitoring in the past few years using PZT transducer is presented.

The reliability of PZT transducer in monitoring of structural damage, such as damage severity identification and damage localization (Yang et. al. 2008), has been studied by many researchers in the past few decades. PZT transducer has shown its great potential in damage detection in many practical applications (Yang and Hu 2008). Sun et al. (1995) first applied the EMI method of modelling active structures to automated real-time structural health monitoring. An index called relative deviation was adopted to quantify the damages through changes in the admittance signatures. However, due to the high frequency of PZT actuation, the detection of damage was found to be localized to the vicinity of the PZT transducer.

Giurgiutiu et al. (1999) adopted the EMI method to study the fatigue testing of a spot-welded lap-shear structural joint at very high frequencies ranging from 200 – 1100 kHz. Giurgiutiu and Rogers (1999b) developed a model for EMI response of a damaged composite beam interrogated by a PZT transducer. However, no systematic characterization was provided for progressive changes in PZT impedance signatures. Later, Park et al. (2000a) published experimental studies for real-time damage detection of civil infrastructures such as composite reinforced concrete walls, pipe joint and the ¼-scale bridge joint earlier investigated by Ayres et al. (1998). Through these experiments, it was also shown that the changes in the impedance signatures due to external noise/ambient conditions such as impact-induced-vibrations, added loading and temperature variations, are small when compared to the changes due to damage induced in the structure.

More recently, Naidu (2004) has presented an experimental based investigation on damage severity identification using PZT transducer. Experiments were carried out on a 1D beam structure and progressive damages were incurred and identified using a single PZT transducer. He established that a single PZT transducer is sensitive enough to detect damages. Hey et al, (2005) published their study on damage localization using multiple PZT transducers through individual and parallel interrogation. Statistical index RMSD was used for quick damage localization and the approximate location of damage was successfully estimated. Use of RMSD index will be discussed in detail in the following section.

2.5 Statistical Index

In the EMI based SHM, changes in the acquired admittance signatures serve as indicators of damages. To characterize different types of damages, it is necessary to adopt statistical measures to quantify it. Samman and Biswas (1994 a and b)

presented a few pattern recognition techniques such as 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. Guirgiutiu and Rogers (1998) used the root mean square deviation (RMSD) between the signatures of the two states as the suitable damage index. Naidu (2004) and Hey et al, (2005) used RMSD index to successfully characterized damages.

Based on the above work, RMSD was chosen as a damage index for this study as well. The RMSD index is a widely used statistical index and it is used in this study as an indicator of different stages of damages in structure. As damages progress along an axial direction, the changes in structure under different damaged stages will be reflected by the RMSD index. The RMSD index is presented herein in the following form:

$$\text{RMSD (\%)} = \sqrt{\frac{\sum_{i=1}^N (y_i - x_i)^2}{\sum_{i=1}^N x_i^2}} \times 100 \quad (2.22)$$

where x_i and y_i ($i = 1, 2, 3 \dots N$) are signatures obtained from the PZT transducer bonded to the structure before and after the damage has incurred.

2.6 Wireless Communication Based SHM

Nowadays, smart materials such as PZT transducers and fibre optical sensors have been widely used in SHM. They have shown excellent capabilities in the evaluation of structural health in terms of damage, deformation and load monitoring. Conventionally, PZT transducers are bonded to the structures and then connected to an impedance analyzer using thin cables, and the length of these cables are limited to a certain range. This limitation causes difficulties in data acquisition when

structure is hard to access. Further more, using long cables could result in inaccurate results. Thus, wireless sensors have been proposed for use in SHM systems in order to overcome these limitations.

Research in developing effective wireless communication based SHM has attracted interests of many researchers and laboratories in recent years (Lynch and Loh 2006, Mascarenas et al 2006). Subramaniam et al. (1997) have presented a wireless health monitoring for the fabrication of MEMS accelerometers, which have interdigital transducers (IDTs) attached on a PZT substrate. The application of these sensors to health monitoring technology has been discussed by Varadan and Varadan (1999) and Varadan (2002). Wireless sensing technology and system frameworks have also been presented by Pines and Lovell (1998). The use of wireless communication for SHM data acquisition was illustrated by Straser and Kiremidjian (1998). Lynch et al. (2003 a, b) extended the work by embedding damage identification algorithm into wireless sensing unit. With the rapid advancement of sensing, microprocessor, wireless technologies, it is possible to assess the benefits from the application of wireless communication technologies in the field of SHM. Lu et al (2005) adopted the developed wireless modular monitoring system (WiMMS) for civil infrastructural health monitoring. Both shake table test and field experiment were conducted to verify the reliability and applicability of the system. Their paper shows that the wireless monitoring system can provide broad application to monitoring and control of civil infrastructures. Mascarenas et al 2006 firstly proposed the use of AD5933 for measuring impedance signatures for SHM and then more investigations on this chip have been presented in the recent years (Mascarenas et al 2007, Park S. et al 2007, Overly et al 2008, Taylor et al 2009). AD5933 is used as part of the wireless sensing system in the present study and detailed discussion will be presented in the subsequent chapters.

2.7 Summary

This chapter reviewed the concept of smart materials and structures and PZT transducer applications in SHM, especially in damage identifications. PZT transducer has been widely used in EMI based SHM due to its self actuating and sensing capabilities, and its excellent sensitivity to structural damages. Research on damage identification using PZT transducers is presented to provide the necessary background for the present research. Additionally, many EMI models (1D, 2D and 3D) have been developed in the past few decades and the 3D EMI model is adopted in this study.

The currently available wireless based SHM technologies are also reviewed in this chapter. With continuous advancing wireless technologies adopted in SHM, PZT transducer could be applied in more practices.

CHAPTER 3 MONITORING OF DAMAGE PROPAGATION USING SINGLE PZT TRANSDUCER

3.1 Introduction

As mentioned in earlier chapters, structural components are subjected to damages during their service life and once damage occurs, it could progressively increase in certain directions. As shown in Figure 3.1, damage usually propagates progressively and may develop in severity which may eventually cause failure of the structure. Therefore, effective monitoring of damage propagation is an important aspect in SHM.

Figure 3.1 Examples of damage propagation in real life structures

This section presents a study on monitoring damage propagation in aluminum plates using the EMI technique. Experiments are carried out on aluminum host structures and single PZT transducer is used to identify increasing damages on the structure. The objectives are listed as follows:

1. To study progressive damages in rectangular aluminum plates along the length and width directions of the plate. The EM admittance signatures are then recorded and analyzed. Changes of EM admittance signatures while damage increasing are studied.

2. To study damage indices (RMSD) for plates for two different directions of progressive damages.
3. To present experimental and numerical study of multiple damages, and to compare between experimental and numerical admittance signatures. A three dimensional EMI model is used to predict and compare with the experimental signatures.

3.2 Experimental Investigation

3.2.1 Experimental setup

The experimental set-up consisted of a Hewlett Packard (HP) LF4192A impedance analyzer (Hewlett Packard 1996), a personal computer equipped with data acquisition software and an interface cable as shown in Figure 3.2. Experiments are carried out on two identical aluminium plate specimens of dimensions listed in Table 3.1. One PZT transducer is bonded at the centre of each specimen as shown in Figure 3.3. Then the PZT transducers are connected to the impedance analyzer for acquisition of admittance signatures for the considered frequency range. PZT transducers of grade PIC 151 (PI Ceramic 2007) are used in this study. The key physical properties of the PZT transducer and aluminium plates are listed in Table 3.2. A program, functional in the HP-VEE 3.0 software environment, is run on the computer to control the operations of the impedance analyzer. Control of the analyzer and acquisition of admittance data are achieved through the GPIB interface card and cable.

Figure 3.2: Experimental setup

Table 3.1: Material properties of PZT transducers

Parameters	Plate X	Plate Y
Size of aluminum plate (mm ³)	300 x 150 x 2	300 x 150 x 2
Size of PZT transducer (mm ³)	10 x 10 x 0.3	10 x 10 x 0.3
Total number of holes	13	6
Damage propagation direction	Along X axis	Along Y axis

Table 3.2: Physical properties of PZT transducer and aluminium plates

Physical Property	Value	
<u>Mechanical</u>	<u>Al</u>	<u>PZT</u>
Density (kg/m ³)	2715	7800
Young's Modulus (N/m ²) × 10 ⁹	68.95	66.67
Poisson ratio	0.33	0.33
Damping constant × 10 ⁻⁹	5	5
Loss factor, η	-	0.023
<u>Electrical</u>		
Piezoelectric strain coefficients (m/V) $d_{31}, d_{32} \times 10^{-10}$	-2.10	
Piezoelectric strain coefficient (m/V) $d_{33} \times 10^{-10}$	4.50	
Dielectric loss factor, δ	0.015	
Electric permittivity, ϵ_{33} (farad/m) × 10 ⁻⁸	1.75	

The two identical aluminium specimens are labelled as Plate X and Plate Y. Holes with diameter of 5 mm are drilled in sequence on Plate X along the X (designated as X1-X13, Figure 3.3) and on Plate Y along Y directions. The first hole was drilled 15 mm away from the edge of the PZT transducer. The space between holes is maintained at 10 mm. Through-out the experimental tests, the plates are placed on foam without any constraints, i.e., free-free boundary conditions are adopted.

Figure 3.3: Damage progression on Plate X

In this study, the sizes of the two host structural plates and PZT transducers, and the location of the sensors on these plates are maintained identical so as to obtain identical pristine state signatures. Furthermore, it is expected that the cause of the differences in the damage state signatures of the two specimens is only because of the difference in the damage direction.

3.2.2 Frequency selection

One advantage of the PZT transducer is that they can be excited to vibrate at high frequencies in the order of kHz (or MHz). According to the recommendation by Sun et al (1995), major vibration modes of the structure should be included and a frequency range with high mode density (large number of resonance peaks) is preferred. Park et al (2003) further recommended that a frequency range ought to be less than 400 kHz to ensure high sensitivity to incipient damage. However for frequency range larger than 500 kHz is unfavourable due to extreme localization, sensing region at this frequency and the PZT transducer will show adverse

sensitivity to the bonding conditions or PZT transducer itself rather than responding to the behaviour of the structure monitored (Hu and Yang 2007). For the present study, frequency range of 0-500 kHz with a scanning step size of 0.5 kHz is chosen.

3.2.3 Experimental results and discussion

A total of 21 sets of admittance signatures are obtained from the experiments i.e., 2 pristine state signatures (for plates X and Y) followed by 13 PZT admittance signatures recorded after each hole is drilled in sequence along X (on plate X) and 6 PZT admittance signatures along Y (on plate Y) directions.

Figure 3.4 shows conductance signatures of Plate X in the frequency range of 0 to 500 kHz. As shown in the figure, plates X and Y, signatures in higher frequency ranges greater than 50 KHz and less than 500 KHz do not result in proper variations and thus higher frequency ranges are not considered.

Figure 3.4 Conductance signatures of Plate X in the frequency range of 0-500 kHz

Therefore, a smaller frequency range of 0 to 50 kHz is selected for detailed analysis. Obvious shifts of resonance peaks are observed in all signatures, which demonstrate the sensitivity of PZT transducer for damage identification. In the considered low frequency range of 0-50 KHz as shown in Figures 3.5-3.8, both of the location and magnitude of dominant peaks change at different damaged states. Moreover, in the frequency range less than 30 kHz, only change in magnitude of dominant peaks is observed. Prominent effects of damages compared to the pristine state are reflected in the admittance signatures in the form of: (i) appearance of new peaks in the signature, (ii) horizontal shifts of the peaks and (iii) changes in magnitudes of the peaks.

(a)

(b)

Figure 3.5 Conductance signatures for Plate X

(a) Frequency range 0-50 KHz (b) peak at 10 kHz

(a)

(b)

Figure 3.6 Conductance signatures for Plate Y

(a) Frequency range 0-50 KHz (b) peak at 10 kHz

(a)

(b)

Figure 3.7 Susceptance signatures for Plate X

(a) Frequency range 0-50 KHz (b) peak at 10 kHz

(a)

Figure 3.8 Susceptance signatures for Plate Y

(a) Frequency range 0-50 KHz (b) peak at 10 kHz

Figures 3.5a-3.6a and 3.7a-3.8a show the conductance and susceptance signatures of pristine and damage states for both plates X and Y. The changes in both conductance and susceptance signatures support the fact that PZT transducer is very good indicator of damage. Further it is observed that the variations of conductance signature as compared to susceptance are very systematic with higher variations in magnitude (see later section). Additionally, the magnitude of a peak observed at frequency 10 kHz continuously decreased with increases in damage severity as shown in Figures 3.5b-3.6b. In contrary to this, there is no such observation noted in the susceptance signatures as shown in Figures 3.7b-3.8b.

3.3 Statistical Comparisons Between Conductance And Susceptance Signatures

As mentioned earlier, from the naked eye, it can be seen that the conductance signatures had resulted in systematic variations as compared to the susceptance signatures for both plates (Figures 3.5-3.8). To further understand the trend of conductance and susceptance signature for damage propagation, statistical method using RMSD index is used.

The RMSD indices for the conductance and susceptance signatures over the considered frequency range (0-50 kHz) are plotted as shown in Figure 3.9 and Figure 3.10. Most of the RMSD values for damage states follow an increasing trend for plate X but there are some sudden drops in value for some damage cases for Plate Y. Two observations are made from these figures, first is that the magnitude of RMSD indices are higher for conductance based RMSD as compared to susceptance based RMSD. This indicates that the conductance is a better indicator than susceptance for the same amount of damage i.e higher the damage index, higher will be the sensitivity for same amount of damage. Second observation made is that the frequency range 0-50 kHz may not be the most appropriate frequency range for indication of damage propagation using RMSD index (Figure 3.9b and 3.10b) especially for plate Y.

(a)

(b)

Figure 3.9 Experimental conductance based RMSD for frequency range of 0-50kHz

(a) Plate X, (b) Plate Y

(a)

(b)

Figure 3.10 Experimental susceptance based RMSD for frequency range of 0-50kHz (a) Plate X, (b) Plate Y

Since 0-50 kHz is not the best range for RMSD index in this study, a thorough study of only conductance based RMSD values for frequency ranges less than 30 kHz as shown in Figure 3.11 is carried-out. This figure shows the RMSD values for different lower frequency ranges like 0-5 kHz, 5-9.5 kHz, 9.5-15 kHz, 15-20 kHz, 20-25 kHz and 25-30 kHz.

(a)

(b)

Figure 3.11 Experimental conductance based RMSD comparisons over different frequency intervals for (a) Plate X, (b) Plate Y

All these ranges do not yield increasing pattern of RMSD values as damage propagated. Apparently, frequency range 9.5-15 kHz yielded consistent increase as

damage propagates for both the plates. The presence of a consistent reduction in magnitude of peak in this frequency range is the reason for such a continuous increment. However, careful analysis shows that the sum of two small frequency ranges, i.e 5-9.5 kHz and 9.5-15 kHz results in frequency range of 5-15 kHz; also yield consistent increasing pattern as the damage propagated (see section 3.5). Hence, based on the analysis of RMSD index over different frequency ranges the best frequency range selected for indication of damage propagation for the present experimental investigation is 5 to 15 kHz for plates X and Y.

3.4 Finite Element Analysis

3.4.1 3D EMI Model

As mentioned previously, 3D model of Annamdas and Soh (2007) is adopted in this study for FEA. Accuracy of the predictive model depends on factors like the mesh size adopted, and accuracy of the PZT transducer and the host structural properties provided by the suppliers, etc. In FEA modelling, the physical properties used are listed in Table 3.2. In this study, 3D based PZT–host structure interaction model, considering both the extensional and longitudinal actuations of the PZT transducer (Annamdas and Soh 2007) is successfully employed which is not done before for damage propagation.

Figure 3.12 shows the mesh of 1mm x 1mm x 1mm, which is adopted in the region of damages and at the centre location of the plate (as shown in Figure 3.12 b) as these areas are critical in the analysis and finer mesh generally ensures higher accuracy. 5mm x 5mm x 1mm mesh is used for the remaining part of the plates. Only half of the plate is modelled since the host structure is symmetrical about X and Y axis. The constraints are defined as shown in Figures 3.12 (a) and (b) to maintain consistency between the experiment and simulation. The actuation force of

the PZT transducer is applied to the host structure by line loads along the edge of PZT transducer, where one of the holes is also indicated.

(a)

(b)

Figure 3.12 3D PZT-Structure interaction model (a) Finite element mesh of undamaged Plate X with unit distributed loads and linear impedances of PZT, (b) Finite element mesh of damage X1 of Plate X

A harmonic analysis (ANSYS 2000) is performed for the frequency range of 0-50 kHz. This resulted in displacements at all the nodes where unit distributed loads are

applied. The summation of the displacements on the respective faces are represented by u_1 , u_2 , u_3 , u_4 and u_6 which are converted to velocities using the following relationship

$$\text{Velocity} = j\omega (\text{displacement}) \quad (3.1)$$

The displacements are the outputs obtained from the dynamic analysis to derive the velocities, linear impedances and vibration coefficients, and then finally the admittance signatures using Eq. 2.20 (Chapter 2). The Matlab program (Matlab 2007) is used to execute the above equations to predict the conductance and susceptance signatures for all the pristine and damage states of both plates.

3.4.2 Predicted results and discussions

In this study, comparisons are made between the experimental and predictive model studies with respect to conductance signatures only, as it is previously stated that the conductance seems to be better indicator than susceptance signatures.

Figures 3.13 and 3.14 show the signatures obtained from the 3-D EMI based predictive model is observed that most of the dominant peaks in the frequency range of 0 to 50 kHz are effectively predicted. Furthermore, the variations of peaks in the predicted signatures (Figures 3.13 and 3.14) are similar to those in the experimental signatures (Figures 3.5 and 3.6). The only difference found is that there is a slight horizontal shift in the peaks of the predicted signatures as compared to the experimental signatures.

(a)

(b)

Figure 3.13 Predicted conductance signatures for Plate X (a) Frequency range 0-50kHz, (b) Peak at 11 kHz,

(a)

(b)

Figure 3.14 Predicted conductance signatures for Plate Y (a) Frequency range 0-50kHz, (b) Peak at 11 kHz

Further investigation is made in narrow frequency range of conductance signatures where a consistent peak is located as similar to that of the experimental signatures.

The narrow frequency range adopted in the experimental studies is 5-15 kHz, and thus it is expected to be the same even for 3D EMI based predictive model.

The peak at 10 kHz in the experimental conductance signatures which decreases continuously in magnitude from damage state 1 -13 for plate X (Figures 3.5 b) and damage state 1-6 for plate Y (Figures 3.6 b) has shifted to slightly higher frequencies (11 kHz for both Plate X and Plate Y) in the predicted signatures (Figure 3.13b and 3.14b). However, still there are continuous decreases in peak magnitude as the damage propagated even in the predicted conductance signatures.

As mentioned before, the accuracy of predictive model depends heavily on the mesh size, shape and other factors. Nonetheless, the predicted signatures are found to be in good agreement with the experimental signatures.

For the considered frequency range (5-15 kHz) the RMSD indices increased continuously with the increase in damage severity for both experimental and predicted signatures. Esteban et al (1997) concluded that the wave intensity decays exponentially after encountering damage due to energy dissipation. Thus the rising trend in the damage index may be attributed to the fact that the dissipation of the elastic waves generated by the PZT transducer increases when the severity of damage increases.

Additionally, modal analysis is also performed and Table 3.3 lists the first 30 mode frequencies (in the frequency range > 10 kHz) of baseline, X1, X2 and X3 for Plate X. The differences of mode frequency among different damaged stages can be clearly seen.

Table 3.3 Modal Frequencies (Hz) for Plate X

Mode Number	Baseline	X1	X2	X3
1	10032	10030	10031	10029
2	10101	10090	10084	10076
3	10370	10367	10366	10367
4	10381	10377	10376	10371
5	10431	10431	10430	10421
6	10574	10566	10566	10567
7	10769	10764	10764	10762
8	10928	10920	10916	10909
9	11061	11059	11061	11058
10	11338	11334	11332	11325
11	11604	11601	11597	11598
12	11674	11664	11664	11658
13	11763	11761	11761	11758
14	11778	11766	11762	11759
15	12068	12068	12066	12066
16	12077	12077	12076	12076
17	12296	12295	12293	12294
18	12544	12544	12543	12533
19	12611	12605	12604	12600
20	12760	12758	12758	12755
21	12935	12928	12927	12918
22	12957	12954	12949	12941
23	13136	13136	13134	13132
24	13143	13143	13144	13142
25	13294	13289	13284	13283
26	13435	13431	13426	13413
27	13461	13457	13450	13447
28	13505	13498	13498	13490

29	13774	13764	13758	13742
30	13840	13834	13833	13825

3.5 RMSD Index Comparison Between Experimental and Predicted Results

In both the experimental and predicted signatures, it is noted that there exists a trend of decrease in peak magnitude as the damage propagated in a narrow frequency range. Additionally, to better understand the trend of signature for damage propagation, RMSD indices are employed.

The RMSD values for predicted signatures in the frequency range of 0-50 kHz are plotted in Figure 3.15. This figure shows similar trend of RMSD variations as shown in Figure 3.9 in the way that, most of the RMSD values shows an increasing trend while damage increases.

(a)

(b)

Figure 3.15 RMSD versus damage propagation (a) Predicted results of Plate X for 0-50 kHz (b) Predicted results of Plate Y for 0-50 kHz

Figure 3.16 shows the RMSD indices calculated from the experimental and predicted signatures for both Plates X and Y in the considered lower frequency ranges. This figure shows an increase in RMSD value as damage propagated for both the predicted and experimental signatures.

(a)

(b)

(c)

(d)

Figure 3. 16 RMSD versus damage propagation (a) Experimental results of Plate X for 5-15 kHz (b) Predicted results of Plate X for 5-15 kHz (c) Experimental results of Plate Y 5-15 kHz (d) Predicted results of Plate Y for 5-15kHz

Even though the predicted RMSD indices show the same trend of variation as compared to the experimental RMSD indices, their magnitudes are not exactly the same. This is because, when damage occurs in any structure, some physical properties such as stiffness and damping coefficient may also change. However, in the FEA modelling, these physical properties are kept as constants for all the cases of pristine and damage states, which may not reflect the actual situation. On the other hand, damping is also dependent on the excitation frequency. Thus, utilization of a frequency dependent damping instead of a constant damping in the FEA modelling would improve the accuracy of numerical prediction.

3.6 Summary

This chapter presented both experimental and predictive EMI model based investigations on damage propagation for plates. Two identical rectangular aluminium plate specimens are considered as host structure and a PZT transducer is surface bonded on each specimen. Firstly, the experimental signatures are obtained and analyzed for damage propagation along the X and Y directions by comparing each damage state signature with the baseline signature. Moreover, the results obtained from the experiments are analyzed qualitatively (i.e by naked eye), and quantitatively by adopting the statistical RMSD index. For the frequency range of 0-50 kHz, there is no proper increasing trend as damage propagated especially for plate Y. For various frequency ranges (less than 50 kHz), RMSD values for the damage states had not followed any increasing trend. There are some sudden decreases in the RMSD values for some damage cases (especially for Plate Y). Thus, a close up inspection of experimental signatures had shown that, in the narrow range of 5-15 kHz, RMSD values increase consistently with damage for both Plates X and Y. Moreover, for both Plates X and Y, the peaks located at 10 kHz indicate a 'consistent' reduction in magnitude with damage propagation (increase in damage

severity). Subsequently, 3-D EMI model is applied to obtain the predicted signatures and are compared with the experimental signatures. The pattern of signature variation in the predicted signatures for various damaged states is found to be similar to that of the experimental signatures. In the predicted signatures, there are horizontal shifts at some of the peaks as compared to the experimental signatures. Further more, the RMSD values for the predicted signatures also had shown a consistent increase with damage propagation, which is similar to that of the experimental signatures. However, there is a slight horizontal shift in the peaks which are located at a bit higher frequency than 10 kHz. The accuracy of the predictive model is dependent on many other factors like mesh size and shape used in the numerical analysis. The present study also demonstrates that conductance could be a better indicator than susceptance for damage propagation studies in an appropriately selected frequency range.

CHAPTER 4 IDENTIFICATION OF SINGLE DAMAGE LOCATION USING MULTIPLE PZT TRANSDUCERS

4.1 Introduction

In EMI based SHM, identification of damage location is of great importance and hence development of quick damage detection method is needed. It has been established that single PZT transducer is sensitive enough to detect occurrence of damage (Naidu 2004). Chapter 3 has presented a detailed study on monitoring damage propagation on rectangular aluminum plates using a single PZT transducer. Both experimental and numerical studies have been carried out and it has shown that, a single PZT transducer is good enough to detect incipient damage and its propagation. RMSD index is a good indicator of damage propagation in certain frequency range. However, it is insufficient to indicate location of damage or its propagation direction by using only one PZT transducer.

The idea of parallel interrogation was proposed and investigated by researchers for damage localization in the past few years and their experimental results have shown the feasibility of locating structural damage using array of multiple PZT transducers. However, verification of these experimental investigations was not carried out. Therefore the objectives of this study are summarized as follows:

1. To carry out experimental investigation on single damage location using multiple PZT transducers. Damage is created on an aluminum plate and is identified using PZT transducer array which is surface bonded on the plate.
2. To verify experimental results using finite element modeling.
3. To analyze both experimental and numerical results quantitatively using RMSD index for quick damage identification.

4.2 Experimental Investigation

4.2.1 Experimental setup and specimen

Experimental setup is similar to the one used in Chapter 3. It comprises of an HP LF 4192A impedance analyzer, a personal computer equipped with data acquisition software and an interface cable. Experiments are carried out on an aluminum plate of 500mm in length, 400mm in width and 10mm in thickness. A total of 9 PZT transducers (designated as PZT1, PZT2 ... PZT9) of dimension 10mm $\times$ 10mm $\times$ 0.3mm, are surface bonded on the plate in the arrangement of a 3 $\times$ 3 matrix as shown in Figure 4.1. Two 5mm diameter holes (X1 and Y1) are drilled near PZT6 and PZT2 respectively with a clear distance of 30mm between the hole and the PZT transducer.

Figure 4.1: Locations of PZT transducers and damages on aluminum specimen

Admittance signatures, consisting of real and imaginary parts, are recorded before and after damages X1 and Y1 are created. As discussed in the previous chapter,

conductance signatures in lower frequency range (less than 100kHz) is better for damage identification as compared to higher frequency range, thus the experiments are carried out in the frequency range of 10 to 50 kHz. In order to capture more resonance peaks, scanning step of 0.1 kHz instead of 0.5 kHz is adopted for this study. Signatures obtained before and after damage X1 and Y1 are compared for each PZT transducer.

4.2.2 Experimental procedure

It has been established by other researchers that the real part (or conductance) of admittance signature is a better indicator of damage. Therefore, only conductance signature is analyzed in this study. 3 sets of signatures are recorded, that is, before damage is incurred which will be the baseline signature, after damage X1 is created and after damage Y1 is created. 4 different interrogation methods are adopted for each set of signature acquisition as listed below:

Method 1 – Groups of 4 PZT transducers

9 PZT transducers are grouped in 4 (designated as G1, G2, G3 and G4) as shown in figure via parallel connection and excited simultaneously.

Figure 4.2 Parallel interrogation of 4 PZT transducers

Method 2 – Groups of 3 PZT transducers in the same column

3 PZT transducers in the same column are grouped via parallel connection and noted as C1, C2 and C3.

Figure 4.3 Parallel interrogation of PZT transducers in the same column

Method 3 – Groups of 3 PZT transducers in the same row

3 PZT transducers in the same row are grouped via parallel connection and noted as R1, R2 and R3.

Figure 4.4 Parallel interrogation of PZT transducers in the same row

Method 4 – Individual PZT transducer

Signatures are recorded for each of the 9 PZT transducers.

Figure 4.5 Individual interrogation of all 9 PZT transducers

Taking all the signatures of the 9 PZT transducers on a one-by-one base, ie using method 4 is very time consuming. The first 3 methods enable a quick identification of damage location as interrogation time is much less. However, the location identified is not precise enough. Method 4 will be useful to identify the precise location of damage effectively.

4.2.3 Experimental results and discussions

The figures in following pages show the conductance signatures obtained using the 4 methods described in earlier sections. The signatures acquired at damaged states and their baselines are plotted in the same figure for clear comparison. For damaged state X1, signatures taken at non-damage state, or pristine stage, are used as baselines while for damaged state Y1, signatures taken after damage X1 created are used as baseline signatures. Similar signature change patterns are observed for the two damaged stage X1 and Y1, therefore only signatures for comparison of baseline and damage state X1 are presented in this section.

Parallel interrogation of PZT transducers in groups of 4

Chapter 4: Identification of Single Damage Location Using Multiple PZT Transducers

Figure 4.6 Conductance signatures of X1 and baseline for group (a) G1 (b) G2 (c) G3 (d) G4

Parallel interrogation of PZT transducers in columns

(c)

Figure 4.7 Conductance signatures of X1 and baseline for group (a) C1 (b) C2 (c) C3

Parallel interrogation of PZT transducers in rows

(a)

(b)

(c)

Figure 4.8 Conductance signatures of X1 and baseline for group (a) R1 (b) R2 (c) R3

From the graphs of signatures acquired using the 3 parallel interrogation methods, obvious deviations of signatures could be observed. Compared to the following

graphs of individual interrogation, parallel interrogations exhibit larger signature changes. This demonstrates higher sensitivity to damage using parallel interrogation rather than using individual interrogation, hence a quick damage location could be estimated using parallel interrogation.

Individual interrogations of all 9 PZT transducers

Figure 4.9 Conductance Signatures of (a) PZT1(b) PZT2(c) PZT3(d) PZT4(e) PZT5(f) PZT6(g) PZT7(h) PZT8(i) PZT9

Signature acquired after damage shows large deviation from the signature obtained at its preceding stage, that is, its baseline signature. These variations are significant for all the PZT transducers which again demonstrate the sensitivity of PZT transducer to structural damage. In order to have a better understanding of the signature changes, root mean square deviation (RMSD) is adopted to quantify the variations of signatures. The results of RMSD index is discussed in the succeeding sections of this report.

4.3 Finite Element Analysis

4.3.1 3D EMI Model

Similar to previous chapter, 3D EMI model by Annamdas and Soh is adopted to obtain the predicted conductance signatures in this study. The physical properties used and equations for calculation are same as that used in Chapter 3 (Table 3.2, Eq2.20).

As the specimen used in this study is large in size, larger mesh size is adopted in the FEA. Figure 4.10 shows one example of the model with only PZT 6 actuated. The aluminum specimen is divided into mesh size of $5\text{mm} \times 5\text{mm} \times 5\text{mm}$ at the region of nine PZT transducers while larger mesh size of $20\text{mm} \times 20\text{mm} \times 5\text{mm}$ is applied for the remaining part since the region of nine PZT transducers is more critical in the analysis. Throughout the experiment, the specimen is supported at four corners only, that is, it is constrained at the four corners. Hence, displacements along Z direction at four corners of the plate are set to zero. Besides, displacement along X direction at point A in Figure 4.10(a) is set to 0 and displacements along all directions at point B are set to 0. This is to make sure the specimen is properly constrained as simply supported. This assumption is almost equal to that of experimental boundary conditions. Linear harmonic loads are applied to the plate along the edges of PZT transducer to simulate the actuation force of PZT transducer.

(a)

(b)

Figure 4. 10 Finite Element Modeling of PZT6 in damage stage X1

After FEA, the predicted signature is also analyzed quantitatively using RMSD index and compared with the experimental results, as shown in the following

section. Numerical modeling of only individual interrogation for damage states X1 and Y1 are carried out as it would be enough for verification of experimental results.

4.4 RMSD Index Comparison Between Experimental and Predicted Results

As mentioned in the previous sections, statistical analysis (especially using RMSD) is an effective way to understand the changes in signature due to damage occurrence. It is sometimes difficult to tell the trend of signature changes by merely examining the raw data, especially when there is a lot of data to be studied which is the case in the present study. Therefore, a thorough analysis using RMSD index for all of the 4 interrogation methods is necessary. The selected frequency range for RMSD calculation is 10-50 kHz since there are many typical signature peaks within this range. The calculated RMSD values are plotted below.

(c)

Figure 4.11 RMSD of X1 using parallel interrogation (a) Method 1 (b) Method 2 (c) Method 3

Figure 4.11 shows the RMSD values for the 3 parallel interrogation methods. It is apparent that the RMSD values of the groups of PZT transducers which are nearer to the damage are significantly higher than those of the groups which are farther. That is, RMSD for group G2 and G4 are much higher than G1 and G3 in the method of using 4 PZT transducers in a group (method 1). In the second method which interrogates PZT transducers in columns, C 3 generates the greatest RMSD and C1 gives the smallest. The third method that interrogates PZT transducers in rows predicts the damage location most accurately in the way that, R1 and R3 generates the same RMSD value and R2 generates the greatest value. With these information obtained using the 3 parallel interrogation method, the location of damage could be easily estimated to be somewhere within the region of column 3 and row 2. However, this location is only an estimated outcome. Further statistical analysis on individual interrogation is necessary.

Figures 4.12 and 4.13 show the RMSD plots for X1 and Y1 of all 9 PZT transducers using individual interrogation for both the experimental and numerical results.

(a)

(b)

Figure 4. 12 RMSD for (a) Experimental results of X1 (b) Numerical results of X1

(a)

(b)

Figure 4.13 RMSD for (a) Experimental results of Y1 (b) Numerical results of Y1

It is apparent from the experimental results that the RMSD values for the PZT transducers which are nearer to the damage are significantly higher than those of the

remote ones. PZT6 generates the largest RMSD after damage X1 and PZT2 generates the largest after damage Y1. This is due to their proximate locations to the damages. Besides, the RMSD values of the PZT transducers which are located symmetrically with equal distance to the damage, for example PZT4 and PZT6 (after damage Y1 is incurred) are considerably close. From the RMSD patterns shown in Figures 4.12 and 4.13, it is not difficult to find the approximate location of the damage. However, it is worth noting that the above RMSD patterns are not sufficient to identify the exact location of the damage, i.e., the distance of damage from the PZT transducer. Further quantitative study on the relationship between RMSD value and the distance of damage from PZT transducer is in progress.

4.5 Summary

This chapter presents an experimental study of damage localization on an aluminum plate specimen using an array of nine PZT transducers. RMSD index is adopted to quantify the deviation of damage stage signature to the baseline signature, and thereby identify the location of damage. From the experimental results of baseline and damage stage, it is observed that the damage can be approximately located by comparing the RMSD values. The PZT transducer which is proximate to the damage generates the highest RMSD value. Furthermore, the RMSD values calculated for PZT transducers which are equally remote from the damage are approximately the same. In addition, 3-D FEA modeling is carried-out to verify the experimental investigation. The RMSD values of numerical results show similar trend as compared to the experimental ones. However, the observations made are only based on two single-damage case which does not reflect real life situations. Therefore, study on multiple damage localizations which is a more representative case in real life is presented in the following section.

CHAPTER 5 IDENTIFICATION OF MULTIPLE DAMAGE LOCATIONS USING MULTIPLE PZT TRANSDUCERS

5.1 Introduction

As previously mentioned, in real life, once damage occurred in the structural components such as columns and beams, it usually propagates along a direction and thus damage severity continuously increases. Chapter 4 has shown the feasibility of damage localization using multiple PZT transducers. However, these studies have only shown the successful cases for single damage localization which is inadequate to reflect the real life situation. Therefore, study on localization for progressively increasing damage would be very useful.

The main purpose of this study is to identify the locations of multiple damages and direction of damage propagations on aluminum plate using PZT transducers array. A number of damages are created on an aluminum plate to study multiple damages identification. Similar to the previous studies, experimental and numerical investigations are conducted and results are analyzed using RMSD index.

5.2 Experimental Investigation

5.2.1 Experimental setup and specimen

The experimental setup consists of a Wayne Kerr 6420 impedance analyzer, an Agilent 34980A switch box, an interface cable and a personal computer with data acquisition software (Figure 5.1).

Figure 5.1: Experimental Setup

The specimen properties are the same as for the study of single damage localization. A series of damages are created on the aluminium plate as shown in Figure 5.2. To monitor both the severity and locations of multiple damages, signatures are recorded before and after each damage incurred.

Figure 5.2 : Details of specimen

There are 8 holes (labeled as X1, X2, ..., X8) in total with diameter of 5 mm drilled in sequence on the aluminium plate. The first hole is drilled 20 mm away from the

edge of the PZT transducer and the space between holes is maintained at 15 mm. Through-out the experiments, the plate is supported at the four corners only without any other constraint.

As described in Chapter 4, 4 different interrogation methods are used in single damage localization. It is feasible to locate the damage using a combination of interrogation methods 2 – 4, and therefore these three methods are used in the multiple damage localization. Conductance signatures in the frequency range of 10 to 50 kHz with sub-step of 0.1 kHz are recorded at the pristine states and at each damaged state.

5.2.2 Experimental results

Theoretically, signatures obtained from PZT transducers which are bonded on the plate symmetrically (e.g. PZT 1 and PZT 7) should be very similar, if not exactly the same. However in practice, it is very difficult to ensure that symmetrically positioned PZT transducers generate exactly same signatures because many factors could affect the experimental results. For example, the bonding conditions between PZT transducer and host structure, changes in environmental conditions including temperature and humidity, variations in material properties of PZT transducers and sometimes human error in the data acquisition process. Figure 5.3 shows two comparisons of conductance signatures obtained from PZT transducers positioned symmetrically (i.e. PZT 2 vs. PZT 8 and PZT 3 vs. PZT 9).

(a)

(b)

Figure 5.3: Comparisons of conductance signatures obtained from (a) PZT2 and PZT 8, (b) PZT 3 and PZT 9

From Figure 5.3, it is apparent that signatures from PZT transducers at symmetrical positions have shown satisfactory similarities in dominant peaks and also peak shifts. This fact confirms the reliability of acquired experimental results.

However, it should be noted that the pattern of signatures obtained from PZT 5 is significantly different from the ones obtained from other PZT transducers. Figure 5.4 shows a comparison of baseline signatures obtained from the 9 PZT transducers.

Figure 5.4: Comparison of baseline signatures obtained from 9 PZT transducers

From the figure, the slope of signature from PZT 5 and magnitudes of its dominant peaks are significantly different from the others. This difference could be caused by inconsistent bonding condition of PZT 5 during the experiment. As a result, the signatures obtained from PZT 5 might not be as reliable or comparable as the signatures obtained from the other PZT transducers.

Figure 5.5 shows one typical close up view of the conductance signatures in the frequency range of 40-50 kHz, where most of the dominant peaks occur, to give a better illustration of the signature variations.

(a)

(b)

(c)

Figure 5. 5: Close up view in the frequency range of (a) 40-50 kHz and two major Peaks at (b) 41.7 kHz and (c) 45.4 kHz

Two of the major peaks are also plotted to show the pattern of peak shifts. It shows that most of the peaks, though not all, reduce in magnitude while damage increases. This fact shows that there is a consistent correlation between damage propagation and signature changes. To better understand this correlation, the signatures were further analyzed statistically in the following section.

5.3 Statistical Analysis of Experimental Results

5.3.1 Individual interrogation

Figure 5.6 shows the RMSD indices calculated for all damaged state signatures obtained from PZT 1 to 9 to examine the correlations between RMSD changes and damage severity changes. Figure 5.7 shows the correlations between RMSD

changes and damage locations. All the RMSD indices in the two figures are calculated for signatures acquired using individual interrogation method (Method 4).

Figure 5.6: RMSD values for each PZT transducer at different damaged states using individual interrogation method

From Figure 5.6, it is clear that, most of the RMSD values show an increasing trend while damage severity increases. However, the increases in RMSD values are not consistent for signatures recorded by all of the 9 PZT transducers. Especially for PZT transducers which are positioned relatively remotely from the damages, i.e. PZT 1 for instance, the RMSD increases are less consistent. It is possible that such inconsistency is due to decrease in sensitivity to damage when the distance between the damage and PZT transducer increases. Nonetheless it is still feasible to monitor the increasing damage severity in this case as multiple PZT transducers are used and most of them (even PZT 5) are reasonably sensitive to the progressive increase in damages.

Figure 5.7 shows the RMSD comparison of the 9 PZT transducers at different damaged states. Amongst the 9 PZT transducers, signature from PZT 5 yields much larger RMSD value than the rest of the PZT transducers. As explained earlier, signatures acquired from PZT 5 might not be as reliable because they show different patterns to the signatures from the other PZT transducers. However, in despite of PZT 5, RMSD values calculated for signatures generated by all the other PZT transducers show consistent correlation to their distances to damage location as expected.

Figure 5.7: RMSD comparison of 9 PZT transducers at each damaged state using individual interrogation method

The RMSD values for PZT transducers which are positioned closer to the damages are larger than those of the remote ones. Amongst the 8 PZT transducers, PZT 6 yields the largest RMSD value at all the damaged states as its distance to the damages is the smallest. Additionally, it is also observed that, the PZT transducers which are positioned symmetrically to the damages yield very close RMSD values as their distances to the damages are equal. Especially for PZT 3 and 9, their RMSD values are consistently very close for all the damaged state. This might be again due to the fact that they are relatively closer to the damages rather than PZT 1 and 7 hence they are more sensitive to the damages.

All these observations show that it is feasible to use multiple PZT transducers to monitor structural damage severity and to localize multiple damages. The correlation between RMSD values and the distances to damages are satisfactorily consistent. In the case of damage propagation, this method could be very useful to identify the propagation direction hence it would not be difficult to find out the location of propagating damage.

However, using individual interrogation method for damage localization is very time consuming and one of the drawback is that, in the case one or more than one of the PZT transducers yield incomparable signatures due to unexpected factors as previously discussed (PZT5), results obtained from these PZT transducers should not be considered. Localization of damage could become very difficult due to lack of reliable information. To overcome this difficulty and enable a faster identification of damage location, parallel interrogation of multiple PZT transducers could be a complementary method.

5.3.2 Parallel interrogation

As earlier explained, use of parallel interrogation method could be very helpful for quick damage localization. From the conductance signatures, parallel interrogation method improves the sensitivity of PZT transducer on damages detection as the magnitudes of dominant peaks are significantly larger than those of the signatures obtained using individual interrogation. From the statistical analysis of individual interrogation signatures, it was observed that the RMSD values are quite small especially for the PZT transducers positioned remotely to the damages at the first few damaged states. Some of them are as low as only 5% which is hardly a convincing indicator of damage.

Figures 5.8 and 5.9 show a few typical examples for plots of the comparisons of RMSD values calculated for signatures obtained using the two parallel interrogation methods as described in Section 4.2. Comparing to the RMSD values calculated for individual interrogation method, using parallel interrogation methods generates larger RMSD values at all the damaged states.

Figure 5.8: RMSD values for PZT groups R1 and R3 at different damaged states using parallel interrogation method

Similar to the plots for individual interrogation, Figure 5.8 monitors the damage severity while Figure 5.9 is for damage localization. It is observed from Figure 5.8 that, similar to the case using individual interrogation, most of the RMSD values follow an increasing trend when damage increases in severity.

(a)

Figure 5.9: RMSD comparison of groups of PZT transducers at different damaged state using (a) Parallel interrogation Method 2 and (b) Method 3

From Figure 5.9, it is apparent that PZT transducer groups which are closer to the damages generate larger RMSD values. For example in parallel interrogation (Method 3), through-out the 8 damaged states, group R2 gives the largest RMSD value. In contrary, the groups which are positioned further away from the damages such as group C1 always give the smallest RMSD value. Additionally, the groups of PZT transducers which are located equally distant to the damages, i.e. groups R1 and R3, generate very close RMSD values. Comparing to individual interrogation (Method 4), the pattern of changes in RMSD value seems to be more consistent when using parallel interrogation method and the time required for data acquisition is much less. Therefore, parallel interrogation could help to speed up the process of damage localization. However, using parallel interrogation methods, the damage location identified is only an estimation. Further information is still required to locate the damage more precisely.

In real life, parallel interrogation methods could be used to quickly identify the approximate damage locations. If necessary, individual interrogation of each PZT

transducer could be carried out as the next step to find out the damage location more precisely.

5.4 Finite Element Analysis

As the properties of specimen and boundary conditions used in the experiments are the same as used in study of single damage localization, the 3D EMI model used is also the same as described in Section 4.3.1. Properties and boundary conditions of the model can be seen in Figure 4.10.

5.4.1 Predicted Signatures and Discussion

In this section, FE modeling is performed to predict the results for all the 9 PZT transducers at the pristine and 8 damaged states using individual interrogation method. The predicted results are compared to the experimental results for verification and they are also analyzed using RMSD to verify the correlation between RMSD and damage severity and location.

Figure 5.10 shows a typical comparison of the predicted and experimental conductance signatures obtained from PZT 6 at all damaged states in the frequency range of 10-50 kHz.

(a)

(b)

Figure 5.10: Comparison of (a) Experimental and (b) Predicted conductance signatures for PZT 6

From this figure, it is clear that the FE analysis is successful as most of the dominant peaks in this frequency range are successfully predicted although there

are still some discrepancies between the two sets of signatures. It is very difficult to predict experimental signatures exactly as many factors could affect the accuracy of FE analysis such as material properties, boundary conditions applied and mesh size adopted in the FE model.

A close up comparison of predicted signatures in the frequency range of 40-50 kHz are shown in Figure 5.11 (a).

(a)

(b)

Figure 5.11: Close up view of predicted conductance signatures in the frequency range of (a) 40-50 kHz and one major Peaks at (b) 49 kHz

One of the major peaks (at 49 kHz) in this frequency range is also plotted to show the peak shifts. It is observed that, similar to the experimental signatures, most of the predicted signatures also show magnitude reduction at dominant peaks when damage severity increases. This observation verified the consistent correlation between signature changes and damage severity. The comparison between experimental and predicted signatures shows that the FE analysis is successful and the predicted signatures are reliable.

5.4.2 Statistical Analysis of Numerical Results

The predicted signatures are analyzed statistically using RMSD index and compared with the experimental results in order to verify the correlation between RMSD values and damage locations and severity changes. Predicted signatures are obtained for all the 9 PZT transducers using individual interrogation method and the

calculated RMSD are plotted in Figure 5.12 for damage severity monitoring and in Figure 5.13 for damage localization.

Figure 5.12: Predicted RMSD values for each PZT transducer at different damaged states using individual interrogation method

In Figure 5.12, it is apparent that the RMSD value increases consistently when damage severity increases and this increasing trend is consistent even for the remotely positioned PZT transducers. The predicted signatures show more consistent correlations between RMSD and damage severity changes because in FE analysis, signatures would not be affected by any undesirable factors such as variation in PZT transducer properties or bonding conditions.

Figure 5.13: Predicted RMSD comparison of 9 PZT transducers at each damaged state using individual interrogation method

Figure 5.13 shows the comparison of RMSD for 9 PZT transducers at different damaged states (similar to Figure 5.6 for the experimental results). The predicted signatures also show a consistent correlation between the RMSD values and damage locations in a similar way as observed in experimental results, i.e. the PZT transducers which are closer to damages generally yielded larger RMSD values. Additionally, the RMSD values for PZT transducers which are equally distant from the damages are very close. The FE modeling has confirmed the observations from experimental results and the consistency of predicted signatures confirmed the feasibility of damage localization using multiple PZT transducers.

5.5 Summary

This chapter presented a study on monitoring of damage severity and damage localization in the case of multiple damages. Both individual and parallel interrogation methods are adopted in the experiments. In the conductance signatures obtained from all the 9 PZT transducers, magnitude reduction of dominant peaks in the frequency range of 10-50 kHz are observed for most of these peaks. This fact shows a consistent correlation between damage severity and signature changes. The changes in conductance signatures are also analyzed quantitatively using RMSD index. The RMSD values, especially the ones for PZT transducers positioned closer to the damages, show a consistent increasing trend when damage severity increases. Besides, the RMSD index is also good for damage localization as the PZT transducers which are nearer to the damages generally gave larger RMSD values than those further away. Additionally, FE modeling is also conducted and the predicted results verified the observations made in the experimental results. It shows reliability of monitoring of damage severity and locations using the proposed methods.

CHAPTER 6 DEVELOPMENT AND APPLICATION OF WIRELESS SENSING SYSTEM USING PZT TRANSDUCER

6.1 Introduction

In the conventional EMI based SHM, sensors such as PZT transducers are bonded to the structures and then connected to monitoring system using cables with limited length. In the case of monitoring large scale structures or where the structure is difficult to access, extensive cables are used and the signatures acquired will be inaccurate due to the resistance of the cables. Therefore, wireless communication based SHM system was proposed to overcome the limitations of the conventional method. Wireless technology plays an important role in health monitoring of aerospace, civil and mechanical structures. It provides a good solution for reducing the cost of labour, controlling the equipments and reducing the time for monitoring of structures.

In this study, wireless communication between the PZT transducers and the analyzer is developed using transmitters and receivers, and the accuracy of signatures acquired is evaluated. In order to evaluate the reliability of the newly developed wireless sensing system, a series of experimental validation tests are carried out. The experiments are conducted to assess the performance of PZT transducers on damage severity and location identification on a beam structure. Signatures are acquired using both wireless and conventional sensing systems, and then compared to evaluate the performance of wireless sensing system.

6.2 Design of Wireless Sensing System for EMI based SHM

The conventional impedance analyzer like Wayne Kerr 6420 is very limited in real life application due to its bulky size and wire connected power supply. The newly developed wireless sensing system is portable and relatively cheap compared to conventional impedance analyzer thus it is more attractive to real world application. The wireless sensing system consists of an Analog Device AD5933, an NXP LPC2136 microcontroller and a radio frequency (RF) transmitter (STR-30) (Figure 6.1). The sensing system is powered by 4 AA batteries.

Figure 6.1: Design of wireless sensing system

PZT transducer bonded to host structure is connected to the wireless sensing unit and admittance signatures are acquired and all the data are transmitted to a PC by the RF transmitter. An STR-30 transmitter is connected to PC via RS232-to-USB interface to receive data. Data acquisition software is installed in the computer to

control the sensing and data transmitting processes. Figure 6.2 below illustrates the working process of this wireless sensing system in practical applications. The wireless sensing system is small and therefore it could be easily installed at the appropriate position. Depending on the surrounding environmental conditions, this system could be used outdoor for an average distance of 100 m.

Figure 6.2: Application of the wireless sensing system

As previously mentioned, a series of validation experiments are carried out to evaluate the reliability of wireless sensing system. The experiments are designed to

monitor the damage severity and location on an aluminum beam structure. Detailed discussion on the validation tests is presented in the following sections.

6.3 Damage Identification In Beam Structure

The previous chapters have discussed in detail on monitoring of damage severity and location using multiple PZT transducers on aluminium plate. The results have shown that it is reliable to use multiple PZT transducers in locating damages and monitoring the severity increases. In this chapter, experiments are conducted to monitor damage location on an aluminium beam. Both conventional and wireless sensing systems are used for data acquisition and results are compared to evaluate the wireless sensing system.

6.3.1 Experimental setup and specimen

The conventional setup is the same as described in Chapter 5 and the wireless setup is discussed in Section 6.2. Experiments are conducted on an aluminium beam and the properties of specimen and PZT transducer are listed in Table 6.1.

Table 6.1: Dimensions of beam and PZT transducer

	Length (mm)	Width (mm)	Thickness (mm)
Aluminum Beam	400	40	2
PZT transducer	10	10	0.3

Two PZT transducers (designated as PZT1 and PZT2) are bonded at 10 mm from the two ends of aluminium beam as shown in Figure 6.3. A number of holes with diameter of 5 mm are drilled on the beam (designated as H1-H22, Figure 6.3). The first hole was drilled 15 mm away from the edge of PZT transducer. The space

between holes is maintained as 15 mm. 5mm diameter bolts and nuts (designated as B1-B22) are installed at all 22 holes on the aluminum beam and all the bolts and nuts are considered as part of the original structure. Throughout the experimental tests, no constraint is applied to the specimen, i.e., free-free boundary conditions are adopted.

Figure 6.3: Aluminum Specimen

6.3.2 Experimental Procedure

In the experiments, the aluminum beam with all holes fixed with bolts and nuts is considered as the pristine state. Admittance signatures at this state are recorded for both PZT1 and PZT2 and the acquired signatures are used as baseline signatures. Structural damage is incurred by taking out the bolts and nuts starting with B1. Signatures acquired from both PZT1 and 2 at damaged state are compared to those baseline signatures. At each damage state, only one set of bolt is removed, i.e. the previously removed bolt (e.g. B1 at damage state H1) is re-installed before continuing with the next damage state (e.g. damage state H2). The focus of this experiment is to monitor damage at different locations on the aluminum beam using the two PZT transducers. Using this method, it is very easy to test specimen with damage at various locations by simply removing the appropriate bolt, rather than creating a number of identical specimens with damage at different location on each

of them. The later method is very troublesome and also suffers from inconsistency in the experiments since it is very difficult to make all the specimens “identical”.

During the experiments, the bolts and nuts are installed to the beam very tightly to make sure a perfect contact between the bolts and aluminum beam. However, in this proposed method, inconsistency might still exist because after one bolt is removed at one damage state, the results obtained for the following damage state could be affected if this bolt is not re-installed to the beam properly. To minimize this error, before recording each damage state signatures, baseline signatures is recorded and compared to the original baseline signatures which is taken at the very beginning of the experiments. If any noticeable discrepancy is observed between the two sets of baseline signatures, the tightness of re-installed bolt must be adjusted until the discrepancy is minimized.

6.3.3 Experimental Results and Discussions

In the experiments, the admittance signatures are recorded in the frequency range of 10-50 kHz and the scanning step is set to 0.1 kHz which is small enough to include the major peaks in the acquired signatures. There are 24 sets of admittance signatures collected, i.e. 11 damaged state signatures and 1 set of baseline signature obtained from each of PZT1 and PZT2. Both the conductance (real part) and susceptance (imaginary parts) are recorded.

Figures 6.4(a) and (c) show plots of conductance signatures obtained from PZT1 and PZT2 in the frequency range of 10-50 kHz. Both horizontal shifts and magnitude changes of peaks about baseline are observed when damage occurred at different locations. For both PZT1 and 2, the dominant peak falls in the frequency range of 45-50 kHz and Figures 6.4(b) and (d) show close-up plot of this dominant peak.

(a)

(b)

(c)

(d)

Figure 6.4: Conductance signatures obtained from (a) PZT1 in 10-50 kHz, (b) PZT1 in 46-50 kHz, (c) PZT2 in 10-50 kHz and (d) PZT2 in 44-48 kHz

It is observed from the above close-up plots that, for signatures obtained from PZT1, the dominant peaks at damaged state shift to the left of baseline, while the peak

shifts to the right for signatures obtained from PZT2. Besides, the magnitude of dominant peaks also changes. However, from these figures it is very difficult to see the pattern of signature changes in response to the damage occurred at various locations. Therefore, statistical analysis is necessary. Further discussion is presented in the following sections.

6.3.4 Statistical Analysis

In this study, the RMSD values are calculated in the frequency ranges of 10-50 kHz (overall) and 40-50 kHz (peak) where the dominant peaks occur. Figure 6.5 shows the RMSD values for signatures obtained from both PZT transducers when damage occurred at H1, H2...till H11.

(a)

(b)

(c)

(d)

Figure 6.5: RMSD values calculated for results obtained from (a) PZT1 in 10-50 kHz, (b) PZT1 in 40-50 kHz, (c) PZT2 in 10-50 kHz and (d) PZT2 in 40-50 kHz

From Figure 6.5, it is apparent that the overall and peak RMSD values change in a similar trend for both PZT transducers. However, some of the overall RMSD values did not follow the general trend of variations. The changes of peak RMSD values are more consistent compared to the overall RMSD values. That is to say, the frequency range within which the dominant peaks fall is more appropriate for damage localization using RMSD index in this case. In the experiment, H1 is the closest damage to PZT1 and H11 is located nearly at the center of beam thus the distances to PZT1 and 2 are approximately the same. For PZT1, as the damage location is getting further away from it the RMSD value decreases. On the other hand, the RMSD increases for PZT2 as the damage is approaching.

It is also observed that, the RMSD values for PZT1 are generally larger than the ones of PZT2. This is consistent to the fact that all the damages are nearer to PZT1. Additionally, the RMSD value of H11 for both PZT1 and 2 are very close (around

55%) which also confirms the fact that H11 is located near the center of the beam. It is easy to locate the damage approximately by analyzing the RMSD values calculated for the two PZT transducers.

6.3.5 Comparison of Results Obtained From Conventional and Wireless Sensing Systems

In order to examine the reliability of the designed wireless sensing system, experiments are carried out on the aluminium specimen which is used in the damage localization test previously. Signatures acquired using wireless sensing system are compared with those obtained from conventional impedance analyzer. 6 tests are conducted in this experiment, i.e. H1, H3, H5, H7, H9 and H11. Comparisons of signatures obtained at 3 different damage states are plotted in Figure 6.6 as below:

(a)

(b)

Figure 6.6: Comparisons of conductance and susceptance signatures obtained from PZT2 using conventional impedance analyzer and wireless sensing system at (a) H1 state, (b) at H5 state and (c) at H9 state

From Figure 6.6, it is apparent that the signatures obtained using conventional impedance analyzer and wireless sensing system are almost the same. All the major peaks are matching in both conductance and susceptance signatures. Same observations are also found in the rest of the validation test results. This shows that wireless sensing system is reliable and it could be very useful in many real life applications.

6.4 Summary

This chapter has presented a newly developed wireless sensing system. Validation tests are conducted to examine the reliability of this sensing system. The validation tests are designed as an experimental study on damage localization using an

aluminum beam structure with bolts and nuts installed. Signatures at damaged state show both horizontal shifts and magnitude changes of peaks about baseline signatures. Conductance signatures are analyzed statistically using RMSD index in the frequency ranges of 10-50 kHz and 40-50 kHz where dominant peaks occurred. For both PZT transducers, the variations of RMSD values show clear trends in response to the changes of damage location in the way that, RMSD value increases when damage approaches the PZT transducer and vice versa. However, the RMSD values calculated in the frequency range of 40-50 kHz is more appropriate in this study since the changes of RMSD values are more consistent as compared to the overall ones. PZT1 which is nearer to the damage generally generated larger RMSD values as compared to PZT2 and when the damage is located at center of the beam, the RMSD values from two PZT transducers are approximately the same. These facts show the feasibility of damage localization by analyzing the RMSD index using multiple PZT transducers. The signatures acquired are comparable to the ones obtained using conventional impedance analyzer, which validates the reliability of the wireless sensing system.

CHAPTER 7 CONCLUSIONS AND FUTURE WORK

7.1 Conclusions and Contributions

The research in this thesis concentrated mainly on monitoring of structural damages in terms of severity and location identification, which are two major concerns in SHM, using PZT transducers. The experimental results and FE analysis which accurately verified the experiments are useful to enhance practical application of PZT transducers. The research further extends the EMI method for wireless sensing which will overcome the limitations of conventional data acquisition methods. The specific research contributions are summarized as follows.

7.1.1 Monitoring of damage propagation

In the study of damage propagation, experiments were carried out on two identical aluminum rectangular plates with single PZT transducer bonded to the center of the plate. Progressive damages were created and signatures were recorded at the pristine and damaged stages. The obtained results were analyzed qualitatively and quantitatively using RMSD index. It was observed that the magnitude of resonance peak at 10 kHz reduced while damage propagates for both Plate X and Plate Y. Further more, the RMSD value calculated over the frequency range of 5-15 kHz was found to increase when damage increases.

In addition to experimental study, 3D EMI model was applied to obtain the predicted signatures and compared with the experimental results for verification. Similar trend of signature changes were found in the numerical results. Consistent reduction in magnitude of resonance peak was observed with damage propagation and there was also an increase of RMSD value in the frequency range of 5-15 kHz.

However, there was a small horizontal shift of the peak, ie, the peak is found to be located at 11 kHz instead of 10 kHz.

7.1.2 Single Damage localization

Chapter 4 presented the study of damage localization using 4 interrogation methods. In this chapter, localization of a single damage was studied. Experiments were carried out on an aluminum plate with 9 PZT transducers surfaced bonded on it in a 3 by 3 array. PZT transducers were interrogated with 4 methods: parallel interrogation of PZT transducers in groups of 4, parallel interrogation of PZT transducer in columns, parallel interrogation of PZT transducer in rows and individual interrogation of all 9 PZT transducers. Signatures were acquired at the pristine stage and after damages X1 and Y1 were created respectively.

Comparison was made between the damaged stage signatures and baseline signatures, and obvious deviations were observed which shows sensitivity of PZT transducer to damage especially using parallel interrogations. To examine the signature deviations clearly, RMSD index was again used. It could successfully estimate the location of damage by comparing the RMSD in the way that, PZT transducer which is proximate to the damage generates the highest RMSD value. Furthermore, the RMSD values calculated for PZT transducers which were equally remote from the damage are approximately the same. FEA using 3D EMI model was also carried out to verify the experimental results and similar results were obtained. Simulation of individual interrogation was included in this chapter.

7.1.3 Multiple Damage localization

On the basis of investigations presented in Chapter 4, further study on damage localization was presented in Chapter 5. The main purpose of this study is to examine the correlation between the RMSD values and damage severity as well as damage location at the same time. Similarly, both individual and parallel interrogation methods were adopted in the experiments. A series of damages were created along certain direction on the aluminum plate and signatures at each damaged states were recorded.

The experiments successfully monitored the increasing damage severity as in the conductance signatures obtained from all the 9 PZT transducers, magnitude reduction of dominant peaks in the frequency range of 10-50 kHz was observed for most of these peaks. This fact shows a consistent correlation between damage severity and signature changes. The changes in conductance signatures were also analyzed quantitatively using RMSD index. The RMSD values, especially the ones for PZT transducers positioned closer to the damages, show a consistent increasing trend when damage severity increases.

Additionally, the RMSD index is also good for damage localization as the PZT transducers which are nearer to the damages generally give larger RMSD values than those that are further away.

To verify the experimental results, FE study was conducted and the predicted results verified the observations made in the experimental study. It shows reliability of monitoring of damage severity and locations using the proposed method.

7.1.4 Development of wireless communication based SHM system

Wireless technology plays an important role in controlling health monitoring of aerospace, civil and mechanical structures. It provides a good solution for reducing the cost of labour wages, controlling the equipments and reducing the time for monitoring of structures.

Chapter 6 introduced a recently developed wireless communication based sensing system. The wireless sensing system consists of an Analog Device AD5933 an NXP LPC2136 microcontroller and a radio frequency (RF) transmitter (STR-30). The sensing system is powered by AA battery and this enables the system to be installed at any place easily.

In order to evaluate the accuracy of this new sensing system, validation tests were conducted. The experiments were designed to monitor different damage locations on a 1D beam structure by installing and removing bolts and nuts onto an aluminum beam. Results were recorded with damage located at different places and RMSD values were used in this study. With this proposed method, the damage location was successfully identified as the RMSD value is proportional to the distance between damage and PZT transducer. From the comparison of signatures obtained from wireless sensing system and conventional impedance analyzer, it was shown that the newly developed sensing system is reliable. It is as capable as the conventional impedance analyzer in damage monitoring.

7.2 Future Work

This thesis has presented study on estimation of occurrence of damage and changes in damage severity and locations. However, to effectively monitor the damage severity changes, an appropriate frequency range must be determined before

monitoring. This could be very difficult as the proper frequency range varies for different structure. Further research is still in need to find an effective way in determining this proper frequency range. More over, a precise method to locate damage is yet to be determined. Future research should concentrate on exploring the quantitative relationship between the acquired admittance signatures and the damages as well as different types of host structure. In this thesis, only aluminum host structure was involved. Investigations on other types of structures such as concrete and steel structures deserve further research.

In this thesis, only RMSD is used as the statistical analysis index. In fact, some of the other statistical index could also be very useful in data analysis, for instance, Covariance and correlation coefficient (CC) and mean absolute percentage deviation (MAPD).

In Chapter 6, a newly developed wireless sensing system was introduced and the validation test has shown its accuracy in data acquisition. However, improvements are still in need to make this system more applicable in the real world situation. For instance, the controlling software could be designed more user-friendly and more functions such as instant data plotting could also be added.

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