Health monitoring of civil structures using piezoelectric materials

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Health Monitoring of Civil Structures Using Piezoelectric Materials

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ABSTRACT

The advent of smart materials such as piezo-impedance transducer (PZT) and optical fiber (FBG) has ushered a new era in the field of structural health monitoring (SHM) based on non-destructive evaluation (NDE). Exceptional advantages such as autonomous, real-time and online, remote monitoring could provide a cost-effective and reliable alternative to the conventional SHM techniques. This is especially useful in the field of civil engineering where the area of monitoring is large and with plenty of inaccessible locations.

Up to date, successful research and investigations conducted on the electro-mechanical impedance (EMI) technique employing piezo-impedance transducer are often laboratory based and mainly theoretical. Real life application of the technique, especially under harsh environment, has frequently been questioned.

In this research project, investigative studies were conducted to evaluate the problems involved in real-life applications of the electro-mechanical impedance (EMI) technique. This is an attempt to reduce the gap between theory and actual application. The studies conducted were mainly experimental based. Numerical verification adopting the finite element method (FEM) was also included where necessary.

Durability of the PZT patch when exposed to nominal construction site's condition and its reliability for long term monitoring on host structures of different materials were carefully investigated through experimental tests. Repeatability of electrical admittance signatures acquired from the PZT patches surface bonded on aluminum structures was found to be excellent up to a period of one and a half years. Signatures' fluctuations occurred for those patches bonded on rock structures were primarily due to the frequent changes in internal humidity of rock. Signatures acquired from concrete structure also suffer constant changes due to the process of curing. However, it is conceived that SHM remains possible with appropriate compensation.

A number of protection methods for the PZT patch were attempted. Silicone rubber was found to be a suitable protection. A novel protection technique capable of overcoming the fragility of PZT patch, especially during installation, was proposed.

The effects of bonding thickness and temperature on the admittance signatures were investigated through various experimental tests involving different structures. It was found that the bonding thickness should preferably be thinner than one-third of the patch to avoid any adverse effect caused by the PZT patch's resonance on the admittance signatures which reflect the host structural behavior. On the other hand, the effect of temperature on the admittance signatures was found to be closely related to the thickness of bonding as increase in temperature would reduce the stiffness of the bonding film thus affecting strain transfer. The empirical temperature compensation technique proposed by Park et al. (1999) was adopted in this study and was found to be excellent in compensating the effect of temperature up to a difference of 50 °C on different materials. It was concluded that thick bonding and high frequency of excitation are undesirable especially at elevated temperature.

Novel numerical simulation of the PZT-structure interaction at high frequency range (up to 1000 kHz) using the FEM was successfully conducted which showed more accurate prediction than the FEA-based impedance model and the impedance based analytical models. This novel model also successfully verified some of the experimental observations.

Ability of FBG based sensors to measure strain was proven to possess accuracy at least as good as the conventional strain gauges. Potential integrated use of both the EMI technique and the FBG based strain sensing technique in SHM was studied through experiment on rock structure. It was envisaged that the advantages of each smart material could be appropriately utilized to complement their respective shortcomings in an attempt to forming a more robust and comprehensive smart SHM system.

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LIST OF SYMBOLS

α	Constant mass matrix multiplier
β	Constant stiffness matrix multiplier
β_j	Constant stiffness multiplier for material, j
C_ϵ	Aging rate of coupling factor
C_k	Aging rate of relative dielectric constant
$[C]$	Damping matrix
d_{31}	Piezoelectric constant of PZT patch
d_c	Strain coefficient tensors (converse)
d_d	Strain coefficient tensors (direct)
$[d^c]$	Piezoelectric strain coefficient tensors (converse)
$[d^d]$	Piezoelectric strain coefficient tensors (direct)
D_3	Electric charge density on surface normal to axis 3 of PZT
D_i	Electric displacement
$[D]$	Electric displacement vector
δ_v	Average vertical shift of admittance signatures
δ_h	Horizontal shift of admittance signatures (shift in discrete frequency)
δ	Electrical loss factor
$\Delta\epsilon$	Longitudinal strain
$\Delta\lambda_{BS}$	Wavelength shift due to longitudinal strain
$\Delta\lambda_{BT}$	Wavelength shift due to temperature
$(\Delta n / n)$	Index of perturbation

ΔT	Change in temperature
E_3	Electric field applied along axis 3 of PZT patch
E_j	Applied external electric field
$[E]$	Applied external electric field vector
$\overline{\epsilon_{33}^T}$	Complex dielectric constant at zero stress
$[\overline{\epsilon^T}]$	Complex dielectric permittivity tensor
η	Mechanical loss factor
f	Frequency
g_{31}	Piezoelectric voltage constant
F_0	Magnitude of force
$\{F\}$	Applied harmonic loading
h	Thickness of PZT patch
i	Reference signature at different frequencies
$I(t)$	Sinusoidal electric current applied at time, t
$\dot{I}$	Derivative of electric current
$\bar{I}$	Electric current (complex notation)
j	Imaginary number
k_{31}	Coupling factor
K_j	Portion of structure stiffness matrix based on material, j
K_ϵ	Temperature sensitivity
K_T	Strain sensitivity
$[K]$	Stiffness matrix
$[K_{II}]$	Random matrix

$[K_{12}]$	Random off-diagonal sub-matrices
$[K_{21}]$	Random off-diagonal sub-matrices
$[K_{22}]$	Random matrix
$[K^d]$	Dielectric conductivity
$[K^z]$	Piezoelectric coupling matrix
κ	Wave number
l	Length of PZT patch
L	Grating length
$\{L\}$	Vector of nodal, surface and body charges
Λ	Grating pitch
λ_B	Bragg wavelength
M	Damage metric
$[M]$	Mass matrix
n	Refractive index
n	Number of data points (in temperature compensation technique)
n_{eff}	Effective refractive index
NMAT	Number of materials with damping input in the analysis
ω	Angular frequency
ϕ	Displacement phase shift (phase angle)
R	Reflectivity
$RMSD$	Root mean square deviation
ρ	Density
ρ_α	Photoelastic coefficient

$R_X(0)$	Auto correlation functions of X
$R_Y(0)$	Auto correlation functions of Y
$\rho_{XY}(\tau)$	Correlation coefficient
s_{11}^E	Elastic constant along axis 1 at zero electric field
$[\overline{s^E}]$	Complex elastic compliance tensor
S_I	Strain of the PZT patch in direction 1
$[S]$	Strain tensor
t	Time
T	Curie temperature
T_I	Stress applied in the direction 1
$[T]$	Stress tensor
τ	Number of horizontal data points shifts
$\tan \delta$	Dielectric loss
u	Displacement
u_i	Reference signature obtained from the intact structure
$\dot{u}$	Velocity
$\{u_1\}$	Real displacement vector
$\{u_2\}$	Imaginary displacement vector
$\{u\}$	Nodal displacement vector
$\{\dot{u}\}$	Nodal velocity vector
$\{\ddot{u}\}$	Nodal acceleration vector
$V(t)$	Sinusoidal voltage applied

$\{V\}$	Vector of nodal electric potential
$\bar{V}$	Voltage applied (in complex notation)
ν	Poisson ratio
w	Width of PZT patch
w_i	Signature acquired from the structure after certain degradation
X_1	Random degree of freedom
X_2	Random degree of freedom
$\bar{Y}$	Complex electrical admittance
$\overline{Y_{11}^E}$	Complex Young's modulus of PZT patch along axis 1 at zero electric field
Z	Mechanical impedance of host structure
$Z_{i,1}$	Baseline admittance signatures at frequency interval i
$Z_{i,2}$	Admittance signatures at frequency interval, i with different temperature
Z_a	Mechanical impedance of actuator
$Z_{a,eff}$	Effective mechanical impedance of actuator
$Z_{s,eff}$	Effective mechanical impedance of host structure
Z_{axx}	Mechanical impedance of actuator in x -direction
Z_{ayy}	Mechanical impedance of actuator in y -direction
Z_{xx}	2-D Mechanical impedance of host structure in x -direction
Z_{yy}	2-D Mechanical impedance of host structure in y -direction
Z_{xy}	2-D Cross mechanical impedance of host structure in y -direction
Z_{yx}	2-D Cross mechanical impedance of host structure in x -direction
ξ	Fiber thermo-optic coefficient

CHAPTER 1 INTRODUCTION

1.1 Background

Since the existence of human being, structures have become an essential part of human life. Historically, safety of the structures emerged to be one of the main concerns during their construction and service for accommodating humans and their properties. In the olden days, design of structures depended highly on experiences as well as trial and error. Thus, the designs could be uneconomical due to excessive use of materials but on the other hand, may not be structurally safe.

Throughout the years of research and development, the rapid advancement in structural design theory and the advancements in engineering materials have resulted in more efficient structures. However, the safety of real life structures remains to be a major challenge for engineers when loadings are accompanied by surrounding factors, such as environmental or human factors which deteriorate the structures, and unpredicted loads such as blast loading. Continuous structural health monitoring (SHM) is thus essential to ensure timely repair and maintenance, in order to preserve the integrity and serviceability of the structure at minimum cost. In case of potential structural failure, early warning could minimize human and property losses.

The conventional non-destructive SHM techniques are broadly classified into two categories, namely global and local interrogation techniques, based on the way of interrogation with the host structure. Each of these techniques is found to be restricted by some inherent limitations. For instance, the global interrogation techniques require large force of actuation which is uneconomical and almost impossible for large structures. Moreover, the outcome only reflects global defects, and is unable to detect incipient but potentially hazardous damages. On the other hand, the modeling and analysis involved in the process can be excruciatingly laborious, if not impossible for complex structures.

Before the application of local interrogation techniques, experienced inspectors are required to conduct periodic visual inspection to search for possible damaged locations. The local interrogation techniques are then applied to pin-point the exact spot. In short, local

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techniques are highly inefficient as they require *a priori* knowledge of the approximate damaged location, which relies heavily on the experience of the inspectors.

The recent advent of smart materials applicable in SHM could alleviate the shortcomings of the conventional techniques. Autonomous, real-time, remote monitoring could become possible with the use of smart piezo-impedance transducers and fiber bragg grating (FBG) based strain sensors as these materials possess distinct advantages such as non-intrusive to host structure, highly sensitive to incipient damage or strain, capable of localizing damage and potentially low-cost with mass production. Their potentials in substituting the currently available non-destructive evaluation (NDE) techniques are intensively explored.

Electromechanical impedance (EMI) technique employing piezoelectric-ceramic (PZT) materials as collocated actuators and sensors is proven to be effective in damage detection and characterization (Sun et al., 1995; Ayres et al., 1998; Soh et al., 2000; Park, 2000; Bhalla, 2001). Most of the researches conducted up to date were laboratory based, as reflected in the available literatures. Practical applications are rarely attempted. Various problems related to the real-life application including the workability, reliability, durability and applicability of the EMI technique are pending to be circumvented before the actual application.

On the other hand, practical applications of FBG based strain sensor is relatively matured. Field application on civil structures have been attempted and proven to be effective. Unfortunately, its mere strain sensing capability impedes the FBG sensor from detecting other form of damages.

1.2 Scopes and objectives

The main focus of this study is to investigate the practical issues related to the application of the EMI technique in SHM of civil structures employing piezo-impedance transducers (PZT patches). Long term consistency and repeatability of the admittance signatures acquired from the transducers under various environmental conditions were investigated to study the reliability of the technique. Appropriate protection for surface-bonded PZT patches against adverse environmental effects was also investigated. Other critical issues related to real life applications of the technique, such as the effect of bonding layer and surrounding temperature

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on the admittance signatures acquired were also examined experimentally. Numerical verifications, through the use of finite element method (FEM) were provided where necessary to support certain experimental observations and to provide better understanding of the behavior of the PZT patch actuation and sensing.

On the other hand, the feasibility of integrated use of smart materials in developing a smart SHM system, such as the FBG based strain sensing technique and the EMI technique was studied. Novel application of EMI technique on rock structure was also investigated.

1.3 Thesis Organisation

This thesis consists of a total of seven chapters including this introductory chapter. Chapter 2 presents a detailed review of state-of-the art in SHM, introduction to the concept of smart systems and materials, description of the EMI technique and the current challenges facing the effective implementation of the technique on real-life civil structures. Chapter 3 discusses the feasibility of employing the EMI technique for long term SHM under various environmental conditions. Consistency of the admittance signatures acquired from the PZT patches was investigated. Suitable protection was recommended accompanied by investigation into its potential adverse effect on the signatures. Chapter 4 presents a series of experimental studies investigating the adverse effects of temperature and bonding on the application of the EMI technique. General observations on the effects and their physical reasons were discussed. Guidelines to minimize the undesirable effects were also suggested. Chapter 5 presents a novel attempt in simulating the PZT-structure interaction at frequency range often used in the EMI technique (in the order hundreds of kHz) adopting FEM, incorporating the PZT patch and the bonding layer. Advantages over the existing analytical model and FEA-based impedance modeling were discussed and verified experimentally. Verifications of certain observations outlined in Chapter 4 were also incorporated. Chapter 6 presents the potential integrated use of smart materials, such as the EMI technique and the FBG based strain sensing technique, to form a more robust smart SHM system. Proof of concept application of the system was attempted on rock structures. Finally, the conclusions

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and recommendations are presented in Chapter 7, which is followed by the author's publication, a comprehensive list of references, and the appendices.

CHAPTER 2 STRUCTURAL HEALTH MONITORING

2.1 Overview of Structural Health Monitoring

Aging and deterioration of a structure is inevitable as a result of repeated or excessive usage, overloading, corrosion due to climatic conditions, lack of maintenance or inefficient monitoring and other unforeseen factors. All these factors contribute to the obsolescence of the structure. If maintenance could not be performed in time, the structure could be rendered unserviceable and even failure, causing loss of lives and properties.

The US Federal Reserve Board has reported that the failure of civil infrastructure systems to perform at the expected level may cause a reduction in the national gross domestic product (GDP) by 1% (Aktan et al., 1998).

Thus, periodical monitoring and maintenance of structures, to ensure their serviceability and safety is essential, especially for the civil structures which are expected to accommodate large numbers of humans for years. Early detection of degradation such as cracks, overstress or overstrain, decay of cement matrix, concrete spalls and corrosion losses is desirable to reduce cost of maintenance and to mitigate potential hazards.

These concerns have subsequently triggered research and development in the area of structural health monitoring (SHM). As a result, various SHM techniques have been continuously developed over the last two decades.

Broadly speaking, structural defect detection and analysis techniques can be divided into two categories, namely destructive and non-destructive evaluation (NDE). Destructive test, such as the pull out test on concrete is generally undesirable as the test itself causes destruction on the structure.

NDE is widely used in the civil engineering community as it is more efficient, cost effective, and easier to apply. Based on the way of interrogation with the host structure non-destructive health monitoring techniques can be classified into global and local interrogation techniques. In a broad sense, both techniques utilize the response of the structure under investigation as an indication of the structural health condition under external excitation, which can be intentionally or naturally induced.

2.2 Global SHM Techniques

In global interrogation techniques, the structure under investigation will be subjected to an externally applied global disturbance/excitation (static force or vibration) in healthy condition and the corresponding responses (displacement, mode shape, modal frequency etc) measured will serve as a baseline. According to structural theory, any subsequent global damages incurred will change the structural parameters (such as stiffness) of the structure. Thus, when the same disturbance is inflicted onto the structure, deviation from the baseline will serve as an indication of damage. Depending on the nature of the disturbance, global interrogation technique can be classified into static and dynamic global interrogation.

2.2.1 Global static response based techniques

A technique based on static displacement response was formulated by Banan et al. (1994). The technique involves applying static forces to structure at certain nodal points and measuring the corresponding displacements. With this, a set of member constitutive properties or structural parameters can then be derived. Any change in the parameters from the baseline healthy state is an indicator of damage. Major drawbacks of this technique arise from its practical implementation, such as difficulty in establishing a frame of reference and tremendous effort involved in the application of loads, large enough to cause measurable deflections. Besides, laborious computations are involved to evaluate the useful information.

Another similar technique based on static strain measurements was proposed by Sanayei and Saletnik (1996). 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, the application on real-life structure remains as tedious. In short, applications of these techniques are too tiresome, expensive and impractical.

2.2.2 Low frequency global dynamic techniques

The principle of application of global dynamic techniques lies in the structural dynamic

theory, following the fundamental concept that damage to a structure changes the modal parameters (Zimmerman and Kaouk, 1994) and mode shapes (Pandey and Biswas, 1994) of the structure. When the entire structure under investigation is excited by a low frequency dynamic actuation (harmonic or impulse), the resulting vibrational responses (displacements, velocities or accelerations) at some discrete points along the structure will enable the derivation of the first few mode shapes and their corresponding natural frequencies. Subsequent damage in the structure will alter its modal parameters and structural parameters, namely the stiffness matrix and the damping matrix. Theoretically, information on damage severity and damage location can also be derived from the structural response. These techniques have obvious advantage over the static response techniques since they are relatively easy to implement.

However, these techniques are essentially based on the low frequency dynamic response of structures involving only the first few modes of vibration. Therefore, only a limited number of modal frequencies and their corresponding mode shape vectors can be extracted. As the stiffness change has different sensitivity to each modal vector, it may not significantly affect some of the mode shapes resulting in certain damages unnoticed.

Moreover, these techniques rely heavily on the measurement of global properties to identify the localized changes. At low frequency, small cracks or incipient damages are unable to significantly affect the global modal parameters to permit effective damage detection. Therefore, the low frequency techniques are not discernible for the detection of relatively small sized cracks. In physical terms, the reason for this is attributed to the fact that the long wavelength stress wave of the low frequency modes is unable to detect small local crack. This deficiency, in fact, exists in all global techniques.

In addition, the procedures involved are also very time-consuming and likely to be contaminated by noise associated with the ambient vibrations (typically less than 100Hz) thereby adding an element of inaccuracy. Reliability and health assessment of these global techniques also requires accurate modeling of the damaged structure and a conservative choice of the limit capacity of the structure, restricting its application to structures of relatively simple geometries. Expensive hardware and sensors such as initial shaking and accelerometer further refrains its real life application.

2.3 Local SHM Techniques

Similar to the global techniques, the local techniques make use of the host structural response as a measure of the degree of damage. However, the local SHM techniques rely on local interrogation with the structure. In other words, instead of investigating the structure as a whole, local SHM techniques detect damages only at specific portion of the structure. Some of the commonly available local techniques are: sonic, ultrasonic wave propagation, acoustic or ultrasound emission, magnetic field analysis, electrical methods, dye penetrant test, impact echo test, eddy currents, X-ray radiography, strain gauge based strain detection, ground penetrating radar (gpr) thermal contours, laser interferometry and neutron radiography. Some of these techniques are briefly discussed in the following paragraphs.

One of the most commonly used technique, ultrasonic inspection, based on elastic wave propagation and reflection, has been well established in the engineering community. The waves are expected to be reflected upon encountering crack and the location of the crack can be estimated from the travel duration of the waves. Despite having higher sensitivities when compared to the global techniques, ultrasonic techniques require large and bulky piezo-actuator to generate ultrasonic waves. For good coupling during the test, the structure will be rendered unavailable throughout the process. Complex data processing forms another drawback of this technique.

The acoustic emission technique utilizes elastic waves generated by plastic deformations, moving dislocations and disbands for damage detection and analysis. Deficiencies such as multiple travel paths from the source and susceptibility of the generated signal being contaminated by electrical and mechanical noise prohibit the efficient use of this technique.

Impact echo test is conducted by introducing a stress pulse into the structure using an impact source. Cracks and disbands in the structure will reflect the propagating waves. This technique is proven to be effective in detecting large-size voids and delaminations but insensitive to small sized cracks (Park et al., 2000).

On the other hand, X-rays poses a health hazard to the inspector. Eddy current does not penetrate deeply into inspected material and thus limited to surface inspection.

Another common drawback of the conventional local techniques is its dependency on the

known vicinity of the fracture damage and essentially, only surface cracks can be detected. This requires knowledge of the approximate location of the damage *a priori*. Normally, before the local techniques could be applied, visual inspection for gross assessment is required prior to the application of the local techniques to pinpoint the damage. These techniques require experienced inspectors to evaluate the external signs of structural damage such as corrosion, wear and visible deterioration.

However, in large scale structure, critical parts of a structure may not be readily accessible. This situation is further aggravated by the requirement of bulky probes or equipments to be carried for inspection. Inspectors are also often exposed to dangerous conditions or uncomfortable working environments. High dependency of visual inspection on experience of inspector, high cost and unsystematic procedures render the technique uneconomical and unreliable.

In general, most of these local techniques work best for assessing the condition of portions of a structure or individual members at selected time but are quite impractical for comprehensive monitoring of large structures with complex geometry. Therefore, an autonomous, real-time, reliable and cost efficient monitoring technique, capable of replacing the conventional ones, is constantly being pursued by SHM researchers.

2.4 Advent of Smart Materials, Structures and Systems in SHM

2.4.1 Background

Technological advancement of mankind is closely related to the evolution of materials. In the olden days, before the emergence of systematic structural design methodology, civil structures were built based on experience or trial and error, which often, resulted in structures been over-designed but may not be structurally sound.

Subsequent development in structural design and materials aimed at achieving a set of intended functions under pre-selected loads or a selection of the dimensions of load-bearing components of the structure. Further research in materials led to the advent of man made materials such as plastics and composites. Successive revolutions then led to the ideas of

embedding sensors to monitor complex strain fields of structures. In recent decades, research and development in materials and structures have witnessed the emergence of a new concept -- “smartness” in materials, structures and systems (Rogers et al., 1988; Takagi, 1996), in which the structure is expected to actively adapt itself to external or internal changes (such as damage) and remains functional.

2.4.2 Smart materials, structures and systems

The concept of smart materials arose from observations on some recently discovered and developed materials which possess unique capability of changing their physical properties in response to certain external stimuli such as temperature, poling direction, electric field, magnetic field and strain. The change in properties can be strain, shape, viscosity, stiffness and damping. When they are properly utilized, their behavior resembles or exhibits certain smartness. Some of them have the ability to transduce energy, acting as sensor or actuator. Suitably incorporating the smart materials in structures and systems will lead to smart structures and smart systems.

Rogers et al. (1988) defined a “smart”, “intelligent” or “adaptive” material as one which possesses extraordinary and useful properties that can be designed and developed into a smart structure. Ideally, smart structure should have the capability to sense, measure, process, and diagnose any change in selected variables at critical locations, and to command appropriate action in a predetermined manner within a certain time frame and ensure the performance of the intended function. An engineered smart structure must meet the following six criteria: functionality, reliability, durability, affordability, safety and cost effectiveness (Srinivasan and McRarland, 2001).

Some of the notable developed smart materials are piezoelectric materials, shape memory alloys (SMA), electrostrictive and magnetostrictive materials, electrorheological (ER) and magnetorheological (MR) fluids, and fiber optics. The following sections briefly describe the properties, applications and limitations of the commonly available smart materials.

2.4.2.1 Piezoelectric materials

When an electric field is applied across the pre-poled direction of a piezoelectric material, deformation occurs in the other two directions. Conversely, it produces a dielectric polarization when subjected to mechanical strain. These unique properties, commonly known as direct and converse effects, enable piezoelectric materials to be utilized as actuators and sensors.

In comparison to other smart materials which possess non-linear characteristics, such as electrostrictive materials and magnetostrictive materials, the piezoelectric effect exhibits linear behavior within certain range. Piezoelectric materials are also less noisy and in general, more efficient. The frequency bandwidth is usually orders of magnitude larger than that of the conventional modal analysis equipment. For these reasons, they are found to be highly desirable for smart system applications. Piezoelectric materials are commercially available in two principal forms, namely, piezoceramics and piezopolymers.

Piezoceramics exhibits most of the characteristics of ceramics, including a high elastic modulus, high rigidity, brittleness and low tensile strength. Efficient conversion of electrical energy to mechanical energy renders piezoceramics suitable for actuation. The most commonly available type of piezoceramics is the Lead Zirconate Titanate (PZT).

On the other hand, piezopolymers are characterized by low charge characteristics. They are electro-mechanically weak when compared to piezoceramics. However, piezopolymers are more sensitive to mechanical loads over a larger range, which renders them to be better sensors. The most commonly available form of piezopolymers is the Polyvinylidene Fluoride (PVDF).

Piezoelectric materials have been successfully implemented in various applications such as vibration control and distributed structural excitations (Zhou et al., 1996; Fairweather, 1998), structural health monitoring (Sun et al., 1995; Ayres et al., 1998; Soh et al., 2000; Bhalla, 2001; Naidu and Soh, 2004; Ihn and Chang, 2004a; Ihn and Chang, 2004b), and systems identification (Liang et al., 1994; Giurgiutiu and Rogers, 1998; Giurgiutiu and Zagari, 2002). Other applications include ultrasonic sensors, piezoceramic stacks, bimorphs, micro-positioning actuators, and controls in robotic systems.

2.4.2.2 Electrostrictive materials

Electrostrictive materials are characterized by the phenomenon known as electrostriction, a phenomenon similar to piezoelectricity in which mechanical deformation occurs upon application of electric field. However, they are isotropic and possess no net polarization. The electromechanical coupling is also non-linear; and the strain generated is approximately proportional to the square of induced polarization at low electric field. Any increase in electric field will lead to asymptotically constant value. Another distinct difference from piezoelectric materials is that it does not generate strain upon the reversal of electric field. Thus, this unidirectional effect limits the application of electrostrictive material for bidirectional actuation.

2.4.2.3 Magnetostrictive materials

Similar to electrostrictive materials, magnetostrictive materials are solids that develop considerable deformation when subjected to magnetic field, and conversely produce magnetic field when mechanically deformed. Magnetostrictive materials can act as actuator as well as sensor. When compared to piezoelectric materials, magnetostrictive materials can produce considerably larger strain. However, the relationship between magnetic field and resulting strain are highly non-linear. They also suffer from problems such as high hysteresis loss, relatively bulky and large in size.

2.4.2.4 Shape memory alloy

As implied by its name, shape memory alloy (SMA) is essentially a kind of metal alloy, which possesses the inherent ability to remember a specific shape. When plastically deformed at low temperature, it can regain its original “memorized” shape when temperature is elevated above certain temperature, called the characteristic transition temperature. One of the most commonly used SMA is NITINOL (an alloy of Nickel, Titanium developed by Naval Ordnance Laboratory).

Restoration of shape can be easily achieved by heating the SMA. Up to four times increase in Young’s modulus and ten times increase in yield strength during the heating process generate large recovery force if they were restrained. Restraining stress of magnitude

100,000 psi allows the SMA to be utilized as actuators.

Active vibration control, active buckling control, shape/motion control, artificial muscle are amongst the applications of SMA. Biocompatibility of SMA enables applications in the biomedical field. Limitations of the materials lie in the difficulty in the control of heating and cooling speed, problem of hysteresis and dissipation of extreme heat within short period.

2.4.2.5 Electrorheological (ER) fluids

Electrorheological (ER) fluid could be viewed as a kind of smart fluid capable of changing its viscosity upon application of external electric field. In the absence of an electric field, the ER fluid behaves like a Newtonian fluid.

The ER fluid is composed of 1 to 100 μ m micro-sized particles dispersed in a carrier fluid, making it a good insulator. Application of electric field forces the particles to form into chains that resist the flow or shear movement, thus changing its flow characteristic. This in turn causes the fluid to undergo significantly large and instantaneous reversible changes in their mechanical properties, such as mass distribution and energy dissipation characteristics. Upon the removal of the electric field, the ER fluid flows smoothly like water. Its reaction time is relatively short, in the order of milli seconds. The main disadvantage of this smart material is that very high voltage is required for effective actuation.

2.4.2.6 Optical fiber

Originally developed for telecommunication purposes, the optical fibers (Gandhi and Thompson, 1992) have recently found their roles as smart sensors. Consisting of glass and silica, optical fibers are very thin fibers which utilize fiber properties for generation of optoelectronic signals, serving as an indication of the external parameters to be measured. Laser diode (LD) or a light emitting diode (LED) is commonly used to generate light signal. At the other end of the fiber, an optical receiver system containing a photodiode will receive the conducted light signal. Any modulation of the light signal (frequency, intensity, wavelength, amplitude, phase, color, modal distribution or polarization characteristics) indicates some disturbances caused by external stimuli (such as strain, pressure, temperature etc.) along the optical fiber. Careful calibration allows the monitoring of the change in

external parameters. Differing from the active smart materials such as piezoelectric materials and SMA, pure sensing based optical fiber is considered as a passive smart material.

Many novel sensors have been developed using optical fibers, such as velocity sensors, pressure sensors, strain gauges (Rao, 1997), temperature sensor (Baran, 1996) and displacement sensors, which find themselves numerous applications in SHM. Distinct advantages of the optical fibers include light weight, non-conductive, rugged and can be easily embedded in composite structures due to their shape adaptability. Moreover, unlike piezoelectric materials, they do not require electrical isolation as they are immune from electromagnetic interference. Ability of multiplexing multiple sensors into a single fiber renders the fiber optics to be space efficient, easy to handle and cost efficient. Among the various types of fiber based technologies, the Fiber Bragg Grating (FBG) is proven to be one of the most versatile (Dewter-Marty et al., 1998; Rao, 1999; Tjin et al., 2002; Lin et al., 2004).

However, multiplexing of a number of sensors into a single fiber suffers from the risk of whole sensor system dysfunctional even when only single damage is incurred at any where along the optical fiber. This problem is exaggerated when the fiber has been embedded inside the materials; where repair is almost impossible. Being fragile, proper protection is very important to ensure its use under harsh environment.

2.4.3 Smart materials: current and future prospects

Smart material applications emerge to be one of the most attractive areas in science and engineering in recent decades. Successful revolutions and applications have been witnessed throughout the years.

Despite its attractiveness, considerable challenges remain in the path towards extensive development and fielding of smart structures and integrated smart systems. Much of the current applications have been limited to individual use of smart materials, and mostly still lingering at the conceptual, embryonic or research stage. Large scale, commercialized and integrated use of several smart materials into a complete and realistic smart structural system which possesses the closed-loop functions of sensing, diagnosing, reacting and restoring are

yet to be achieved. More rigorous research into fundamental problems such as resolving the inherent limitations of the materials, improving design methodology, manufacturing technology, investigating the potential integrated use, and enhancing the practicality and economy are therefore essentials.

2.4.4 Application of smart materials in SHM

Ideally, an intelligent structure is one which is capable of monitoring its own health and preferably performing self-maintenance to retain its functionality upon detection of malfunctions. It is expected that the intelligent structure would possess an integrated package with a monitoring system consisting of sensors, data acquisition, control and communications hardware, and relevant software to perform the intended functions. Successful application of such system is conceived to lead to significant cost savings and enhancement in safety with the autonomous and real time operation.

Despite the fact that the current technology is still in the embryonic stage, SHM techniques employing smart materials such as piezoelectric materials and optical fiber were proven to be robust in damage detection and strain measurement. They were also found to be able to overcome most of the shortages present in the conventional techniques. Detailed descriptions of the optical fiber and the piezoelectric materials, which are the main focus of this study, are presented in the following sections.

2.5 Fiber Optics

2.5.1 Introduction

Light conduction in optical fiber resembles electricity conduction in copper wire. In the early days, optical fiber was found to be advantageous in transmitting data such as telephone conversation, television programs and numerical data throughout long distances with very little signal loss or interference.

Recently, a new application of optical fiber as a sensor in sensing physical parameters such as strain, temperature (Baran, 1996), pressure and vibration (Michel et al., 1996) in

structural components, has enabled itself to be designated as a smart material (Gandhi and Thompson, 1992; Rao, 1997). Other applications such as chemical sensing, crack detection have also been reported in the literatures.

2.5.2 Physical properties and fundamentals of optical fiber based sensors

When light waves travelling in one medium encounter another medium, the angle of incidence will be equal to the angle of reflection with no loss in transmission if the incident angle is larger than certain critical angle. This phenomenon is known as total internal reflection. A cladding (outer layer) of lower refractive index than its core (inner layer) is required to ensure the propagating light waves are “trapped” inside the fiber due to total internal reflection.

Employing an optical transmitter system, an appropriate light signal is created from an electrical signal. The light is then guided into the fiber and transmitted to the other end containing an optical receiver system. The light signal, modulated by external stimuli along the fiber is then converted back to electrical signal for processing and analyzing. Therefore, measurement of external excitation is achieved by measuring the physical properties of the light signal modulated by the external stimuli. This intrinsic sensing capability of optical fiber enables the measurement of external parameters such as strain, temperature, pressure, chemical content etc. through changes in the light's properties including frequency, intensity, amplitude, wavelength and color.

2.5.3 Manufacturing of optical fibers

Optical fibers are usually made up of glass (SiO_2) which is a high index material mixed with various dopants for the control of its refractive index. The core is surrounded by cladding, which is also glass with lower refractive index (0.001 or 0.002 lower). The core of fiber is made up of extremely low-impurity silica and the cladding is typically fluorine-doped glass $125\mu\text{m}$ in diameter. Two types of optical fiber, single mode and multimode fibers are commonly available, each possesses different diameter.

2.5.4 Advantages of fiber optics as sensors

One of the distinct advantages of optical fiber is its ability to sense numerous physical perturbations through a single fiber. Its dual role where the sensor itself is also a transmitter greatly reduces the hassle of wiring. Besides, it can be readily embedded into structure with geometrical flexibility, low heat generation, light weight (specific gravity of silica to copper = 2.2 : 8.9), non-intrusive, unaffected by electrical or magnetic interference, chemically inert, low attenuation and able to withstand harsh environment with little performance degradation.

An ultimate tensile strength of 8×10^5 psi, Young's modulus of 1×10^6 psi (closed to aluminum) and ability to sustain high strain (8%) facilitate the application of optical fiber in strain-sensing. With appropriate adhesive and coating (such as polyimide), fiber optics strain sensors have much longer life-span than the conventional strain gauges, and are able to sustain up to one million cycles.

2.5.5 Fiber optic strain sensors

Optical fiber has overwhelming potential as a strain sensor to replace the conventional strain gauges. Fiber optic strain sensors can generally be classified as interferometric, polarimetric and modal interferometric sensors (Gandhi and Thompson, 1992). Several fiber-optic strain sensors, each of different underlying principles, are briefly described (Srinivasan and McRarland, 2001):

2.5.5.1. Microbent and graded-index fibers

Deformation of structure imparts strain to elastic fiber which changes optical characteristics such as optical intensity and phase. Phase change measured between reference signal through a fiber and another signal coming through a similar fiber having microbends (allowing lights to radiate out) along its length serves as an indication of deformation. Behavior of light signal through this is also influenced by temperature, acceleration and strain.

2.5.5.2. Extrinsic fabry-perot sensor

Extrinsic fabry-perot sensor (Srinivasan and McRarland, 2001) comprises of a single mode fiber and a multimode fiber with a 4mm air gap in between. When securely adhere to the host structure, any changes in length will be transmitted to a change in length of gap. This will, in turn, cause a phase change between the light of the reference signal and the light from the sensing signal because of interference between the two reflections. Thus, the phase change serves as a measure of motion at the gap location and is a basis for an accurate measurement of strain.

2.5.5.3. Mach-Zehnder interferometers

Mach-Zehnder interferometers works on the principle of elasto-optic effect (optics influenced by fiber deformation) through a two-arm optical-phase bridge. With two similar arms, one arm of the bridge is protected from the stress field while the other arm is subjected to deformation from host structure. The refractive index of exposed arm changes with strain, thus altering the phase of the light propagating through it. When the two beams of lights are recombined, the combined wave amplitude will be affected by the phase difference and serves as a measure of the strain amplitude.

Multiplexing of sensor (more than one sensors distributed in series throughout single optical fiber) is possible by varying the length of one arm in each of the series of interferometers. Each arm can be identified through their path-length difference of the optical bridges. This type of sensor is very sensitive (sensitivity up to 10^{-8}). They are effective even in electrically noisy environments.

2.5.5.4. White light interferometry

In this technique, two fibers are spliced together; one is subjected to strain (active) and the other unstrained (passive) serving as a reference. With a broadband (white) light signal sent into both of them, the reflection from the ends of both fibers will interfere with each other in a manner depending on their relative lengths, which varies as the active fiber is strained.

2.5.5.5. Fiber Bragg Grating sensors

Optical fiber when written with closely spaced parallel lines (Bragg Grating) onto a small length (typically 1 to 20mm) of the core of fiber, with the intention of creating perturbation of the core's refractive index is known as Fiber Bragg Grating (FBG). This spatially periodic variation of refractive index acts as a filter which reflects certain wavelength of light (Bragg wavelength) while allowing others to pass through. Any mechanical strain in the fiber will shift the Bragg wavelength through expansion/ contraction of the grating periodicity and the photo elastic effect. Typical gratings have resonant wavelength of 400 to 2000nm.

In the following section, the most versatile fiber optic sensors (Tjin et al., 2002), namely Fiber Bragg Grating (FBG) are discussed in details.

2.5.6 Fiber Bragg Grating

2.5.6.1 Background

Recent emergence of Fiber Bragg Grating (FBG) as strain and temperature sensors has demonstrated distinct advantages such as potentially low cost and unique wavelength-multiplexing capacity over other fiber-optic sensors (Rao, 1999). Its excellent long term stability, resistance to various environmental conditions and high reliability reveal its potential SHM application in the field of civil engineering (Lin et al., 2004). It is conceived that wide range of applications, high demand, commercialization and mass production in the near future will render the FBG sensors more economical.

2.5.6.2 Fabrication of FBG

FBG is an optical fiber with a Ge-doped segment written on single mode fiber, where periodic modulation of the core refractive index is formed by exposure to a spatial pattern of ultraviolet light in the region of 244 - 248nm (Rao, 1997). Diameter of FBG ranges from a few μm to a few hundred μm . Reflectivity of the grating is normally high, sometimes approaching 100%.

Figure 2.1: Fabrication of FBG sensors.

Rao (1997) summarized the requirements for fabrication of high quality and low cost FBG sensors. Flexibility, good physical and optical qualities, good repeatability and economical mass production capability are among the elementary requirements. For good sensor performance, the interrogation technique for data acquisition turns up to be essential when dealing with precise measurement of FBG wavelength shift. Other requirements include high resolution with large measurement range, cost effective when compared to the conventional sensors and be compatible with multiplexing.

2.5.6.3 Sensing principles

When a broadband light source is passed through the FBG, interaction of the beam of lights with the gratings will result in reflection of a single wavelength, known as the Bragg wavelengths with the rest passing through the gratings. The Bragg wavelength, λ_B , is related to the grating pitch, Λ and the effective refractive index, n_{eff} of the grating by

$$\lambda_B = 2\Lambda n_{eff} \quad (2.1)$$

The reflectivity of the Bragg wavelength caused by the gratings can be estimated (Rao, 1997)

$$R = \tanh^2 \Omega \quad (2.2)$$

where

$$\Omega = \pi \left(\frac{L}{\lambda_B} \right) \left(\frac{\Delta n}{n} \right) \eta(V) \quad (2.3)$$

The factor $\eta(V) \approx 1 - 1/V^2$, $V \geq 2.4$ is the fraction of the integrated fundamental mode intensity contained in the core, V is the normalized frequency of the fiber, n is the refractive index, L is the grating length and $(\Delta n / n)$ is the index of perturbation.

FBG sensor has found its applications in strain, temperature, pressure and dynamic magnetic field measurements. The fundamental sensing principle lies in the Bragg wavelength shift due to expansion / contraction of the grating periodicity and the photo elastic effect corresponding to the alteration of the abovementioned parameters.

Equation 2.3 shows that the reflectivity is directly affected by the grating length and index of perturbation which is in turns dependent upon the exposure time and power of the UV radiation for each specific fiber.

One of the obvious differences between the FBG based sensor and the conventional fiber optic interferometric sensor is its broadband light source with high resolution wavelength shift detection system instead of conventional high coherent lasers. To ensure large range of resolution, the light source required usually possesses a wide wavelength bandwidth and high optical power. Some examples of the light sources (Rao, 1997) are edge-emitting light emitting diodes (ELED), superluminescent diodes (SLD), superfluorescent fiber sources (SFS) and tunable fiber lasers (TFL). The optical power ranges from $1 \mu W$ to $10 mW$.

2.5.6.4 Strain sensing

When subjected to longitudinal strain, $\Delta \epsilon$, the corresponding wavelength shifts due to change in Bragg grating can be expressed as (Rao, 1997):

$$\Delta \lambda_{BS} = \lambda_B (1 - \rho_\alpha) \Delta \epsilon \quad (2.4)$$

where ρ_α is the photoelastic coefficient of the fiber, given by

$$\rho_\alpha = \frac{n^2}{2} [\rho_{12} - \nu(\rho_{11} - \rho_{12})] \quad (2.5)$$

where ρ_{11} and ρ_{12} are the components of the fiber-optic strain tensor and ν is the Poisson ratio. It should be noted that measurements of acceleration, ultrasound and force are also applicable

as all these can be converted from strain.

Linearly chirped FBG can act as a wavelength bandpass filter device, where the pitch of the grating is varied along the position of the grating length, and the chirped FBG can reflect a large number of wavelengths. This type of FBG possesses advantages in dynamic strain sensing.

2.5.6.5 Temperature sensing

Wavelength shift, $\Delta\lambda_{BT}$ due to variation in temperature ΔT can similarly be expressed:

$$\Delta\lambda_{BT} = \lambda_B (1 + \xi) \Delta T \quad (2.6)$$

where ξ is the fiber thermo-optic coefficient. Sensitivity of strain measurement and temperature measurement is discussed in (Rao et al., 1995).

Pure strain sensing application can often be affected by the effect of temperature, especially for quasi static and static strain measurement. Thus, to be used as strain sensor (in the absence of pressure), a temperature compensation technique is required. Some of the techniques useful in separating the two parameters are described below.

I. Reference FBG method

A strain-free FBG, acting as a reference, is placed in adjacent to a similar strain-sensing FBG (attached to host structure). With the strain change of the reference FBG, the pure strain of the structure can be obtained by subtracting from the total wavelength shift. This is considered as one of the simplest and most direct ways for temperature compensation during strain measurement.

However, it was found that chirped FBG in a tapered optical fiber can solve this problem (Rao, 1997). It can be independent from the environmental temperature. This is achieved when a taper profile is designed such that the FBG is linearly chirped when tension is applied, which results in a strain gradient along the FBG. Instead of measuring the change in Bragg wavelength, the effective bandwidth variation is acquired. In this case, the reflected intensity signal is insensitive to temperature. However, the tapered region of the fiber suffered from the problem of low mechanical strength. Further investigations into the measurement accuracy are also required as fluctuation of intensity along the fiber can lead to measurement errors.

II. Dual-wavelength FBG

Two sets of wavelength-shift data are used from two superimposed FBGs written at the same location in the fiber. By assuming a linear shift in wavelength when subjected to both temperature and strain, the Bragg wavelength-shift, $\Delta\lambda_{BT}$ is related to alteration in temperature and strain as:

$$\Delta\lambda_{BT} = K_\epsilon \Delta\epsilon + K_T \Delta T \quad (2.7)$$

where K_T and K_ϵ are the strain and temperature sensitivities of the FBG respectively. The assumption of this equation is that the strain and temperature are independent of each other, which is true under the condition of small perturbation.

Therefore, the strain and temperature can be conveniently evaluated by solving the simultaneous equations, in matrix form:

$$\begin{pmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{pmatrix} = \begin{pmatrix} K_\epsilon & K_{T1} \\ K_\epsilon & K_{T2} \end{pmatrix} \begin{pmatrix} \Delta\epsilon \\ \Delta T \end{pmatrix} \quad (2.8)$$

where 1 and 2 indicate the two referred wavelengths. K matrix can be determined through experimental measurement of the wavelength shift due to strain and temperature separately.

Another possible way of obtaining two sets of wavelength data is to make use of the first harmonic resonance of FBG. It is however note worthy that both dual-wavelength superimposed FBG method and harmonics method require two sets of independent detection systems. One interrogation system with FBG and another temperature measurement system are to be used for acquiring the corresponding wavelength shift. This may lead to unnecessary raise in cost and complication of measurement system.

III. Superimposed FBG and polarization-rocking filter method

A photosensitive D-type polarization-maintaining fiber can be fabricated by using external point to point writing technique (Rao, 1997). A Mach-Zehnder fiber interferometer is made by arranging two rocking filters on the same piece of fiber at a certain separation, which can be used for temperature measurement.

The temperature-induced resonant wavelength shift is about two orders larger in magnitude than for the normal FBG. Therefore, a K matrix similar to Equation (2.8) can be obtained for separation of temperature and strain due to the fact that the wavelength-shift

coefficients in temperature and strain for both materials are different.

Despite avoiding the use of two wavelengths during the measurement, this method suffers from a few constraints such as large difference in length between rocking filter and normal FBG, lower accuracy and limited multiplexed sensors due to much wider bandwidth of rocking filter and extra cost for polarization maintaining fiber and related devices.

IV. Combined FBG and long-period grating

Originally developed for optical fiber communications systems as a band rejection filters, long-period fiber grating is generally similar to FBG besides its long-period grating which can sometimes be hundred times larger than Bragg grating (Rao, 1997). Long-period gratings have different strain and temperature wavelength response coefficients when compared with Bragg gratings. Measurement of strain and temperature can be simultaneously achieved if the strain and temperature wavelength response coefficients of both gratings are known.

This method does not require two sets of independent detection systems which makes it much more convenient than the dual-wavelength superimposed FBG method.

2.5.6.6 Applications of FBG

Multiplexing of FBG is mandatory for a cost and labor effective practical application. This is especially useful during quasi-distributed measurement. It was found that most of the multiplexing schemes adopted for the conventional fiber-optic sensors can be applied to FBG. Some of the commonly used multiplexing schemes include wavelength-division-multiplexing (WDM), time-division-multiplexing (TDM), spatial-division-multiplexing (SDM) and 2-D multiplexing topologies.

Successful application of FBG in health monitoring has been proven (Storoy et al., 1997; Tjin et al., 2002; Lin et al., 2004), especially in quasi-distributed measurements of strain and temperature. Other applications such as cure monitoring of composite materials (Dewynter-Marty et al., 1998), strain mapping of advance composite materials, bridge strain monitoring (Storoy et al., 1997), temperature measurement in machinery, acceleration measurement have been studied and proven to be applicable.

2.6 Piezoelectricity and Piezoelectric Materials

2.6.1 Background

The discovery of piezoelectricity (Schwartz, 2005) can be traced back to 1880 when Pierre and Jacques Curie were studying the effects of pressure on the generation of electrical charge on a group of crystals such as quartz, tourmaline, and Rochelle salt. They found that these crystals developed electrical charges on their surface when mechanically deformed in the orthogonal direction. Converse effect was also found to present where deformation occurred when a potential difference was applied across certain direction. W. Hankel suggested the term “piezoelectricity” in describing this behavior in 1881, where *piezo* means pressure in Greek. At that time, limited performance of these materials inhibited their commercialization. This situation persisted until a major breakthrough came with the discovery of piezoceramics, namely Barium Titanate and Lead Zirconate Titanate (PZT) in the 1940s and 1950s respectively. These families of materials exhibit much higher dielectric and piezoelectric properties. In 1960s, success of the Japanese companies in developing new processes and applications of piezoelectric devices officially opened their commercial market.

2.6.2 Fundamentals of piezoelectric materials

Piezoelectric effect occurs in certain anisotropic crystal, where the crystal lattice do not have any center of symmetry. In this non-centro symmetric crystal, net dipole moment will be induced upon deformation of the crystal. On the other hand, converse effect where electric field induces mechanical strain is similarly present.

Piezoelectric material is isotropic and does not possess the piezoelectric properties when it is first manufactured, as their electric dipoles are arranged in random directions. Net reactions of the randomly arranged dipoles tend to cancel out each other upon the application of an external electric field.

For the material to exhibit piezoelectricity, a process known as poling is required to permanently align all the dipoles in certain direction. To achieve this, the piezoelectric material is first heated to a transition temperature known as Curie temperature. Above this

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temperature, the dipoles in the solid phase material are free to be re-orientated. Maintaining at this temperature, an intense electric field ($> 2000 \text{ V/mm}$) is applied across the desired direction (polarization direction) to align the dipoles. With the electric field maintained, the temperature is reduced below Curie temperature. As a result, all dipoles are permanently fixed despite the removal of electric field.

Subsequently, application of a small electric field across the poling direction will cause a collective response of all the dipoles and lead to macroscopic expansion along the poling axis and contraction in the perpendicular axis (or vice versa depending on the direction of applied electric field). This is generally known as converse piezoelectric effect. On the other hand, direct piezoelectric effect exists where induction of mechanical strain generates potential difference across the poling direction. From molecular point of view, piezoelectricity arises from the displacement of ions in the crystal lattice when the polarized material is deformed mechanically.

2.6.3 Piezoelectric constitutive relations

The direct and converse piezoelectric effects involve cross coupling interaction between mechanical and electrical behavior of the piezoelectric material. They can be modeled accordingly by linear constitutive equations involving two mechanical variables and two electrical variables (IEEE standard, 1987):

$$D_i = \overline{\varepsilon}_{ij}^T E_j + d_{im}^d T_m \quad (2.9)$$

$$S_k = d_{jk}^c E_j + \overline{s}_{km}^E T_m \quad (2.10)$$

Equations (2.9) and (2.10) can be expressed in generic terms as a compressed matrix notation:

$$\begin{bmatrix} D \\ S \end{bmatrix} = \begin{bmatrix} \overline{\varepsilon}^T & d^d \\ d^c & \overline{s}^E \end{bmatrix} \begin{bmatrix} E \\ T \end{bmatrix} \quad (2.11)$$

where $[D]$ (C/m^2) is the electric displacement (charge density) vector, $[S]$ is the second order strain tensor, $[E]$ (V/m) is the applied external electric field vector and $[T]$ (N/m^2) is the stress

tensor, $[\overline{\varepsilon}^T]$ (F/m) is the second order complex dielectric permittivity tensor under constant stress, $[d^d]$ (C/N) and $[d^c]$ (m/V) are the third order piezoelectric strain coefficient tensors (the superscripts d and c indicate the direct and converse effect respectively), and $[\overline{s}^E]$ (m^2/N) is the fourth order complex elastic compliance tensor under constant electric field.

It is clear that two basic equations could readily be refined from the constitutive equations. When no stress is applied, Equation (2.9) is interpreted as an electrical expression indicating a material subjected to electrical field having electric displacement. Equation (2.10) can be reduced to a material's stress-strain relationship at zero field strength. Thus, the piezoelectric effect is governed by the piezoelectric strain coefficient, d , which appears in both equations. $[d_c]$ defines the strain per unit field at constant stress, while $[d_d]$ defines the electric displacement per unit stress at constant electric field.

Mechanical and electrical behavior of the piezoelectric material can be expressed using a well accepted set of conventions indicating various directions. A commonly used rectangular piezoelectric plate as shown in Figure 2.2 is taken as an example for description.

Figure 2.2: A piezoelectric element with conventional labels of axes.

The poling direction is normally along the thickness direction, denoted as axis-3. Therefore axis-1 and axis-2 indicate the plane of the piezoelectric sheet. Taking advantage of symmetry of the stress and strain tensor, the original matrix can be reduced to a more concise (6x1) vector form: $[T] = [T_{11}, T_{22}, T_{33}, T_{23}, T_{31}, T_{12}]^T$ and $[S] = [S_{11}, S_{22}, S_{33}, S_{23}, S_{31}, S_{12}]^T$ respectively. The piezoelectric strain coefficients can accordingly be reduced to second order tensors, as $[d_d]$ (3x6) and $[d_c]$ (6x3) with $[d_d] = [d_c]^T$. Piezoelectric strain coefficient varies with different types of crystal structures. The matrix $[d_c]$ of the commonly used Lead

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Zirconate Titanate, PZT is:

$$d_c = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (2.12)$$

The first subscript indicates the direction of externally applied field whereas the second subscript denotes the plane of resulting strain with 4 and 5 indicating the shear strain in plane 2-3 and plane 1-3 respectively. Shear in the plane 1-2 will not generate any electrical response and is thus excluded in the equation. This also implies that application of electric field in any direction will not cause shear strain in plane 1-2. For good sensing capability, the algebraic sum of d_{31} and d_{33} should be maximized, whereas ϵ_{33} and the mechanical loss factor should be minimized (Kumar, 1991).

The compliance (inverse of Young's modulus or shear modulus) matrix could be expressed as:

$$\overline{s^E} = \begin{bmatrix} \overline{s_{11}} & \overline{s_{12}} & \overline{s_{13}} & 0 & 0 & 0 \\ \overline{s_{21}} & \overline{s_{22}} & \overline{s_{23}} & 0 & 0 & 0 \\ \overline{s_{31}} & \overline{s_{32}} & \overline{s_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \overline{s_{44}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \overline{s_{55}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \overline{s_{66}} \end{bmatrix} \quad (2.13)$$

The electric permittivity matrix (for PZT) can be written as:

$$\overline{\epsilon^T} = \begin{bmatrix} \epsilon_{11}^T & 0 & 0 \\ 0 & \epsilon_{22}^T & 0 \\ 0 & 0 & \epsilon_{33}^T \end{bmatrix} \quad (2.14)$$

The electric displacement vector and electric field vector are unaffected by the simplification:

$$D = \begin{bmatrix} D_{11} \\ D_{22} \\ D_{33} \end{bmatrix} \quad (2.15)$$

$$E = \begin{bmatrix} E_{11} \\ E_{22} \\ E_{33} \end{bmatrix} \quad (2.16)$$

2.6.4 Classifications of piezoelectric materials

Nowadays, piezoelectric materials are commercially employed in various applications such as medicine, military, communication and automobile. As a transducer, its electro-mechanical property continues to attract considerable attention from a wide range of research communities. Two commercially available piezoelectric materials, piezoceramics and piezopolymer are described in the following sections.

2.6.4.1 Piezoceramics

The most commercially available piezoceramics possess a perovskite structure as shown in Figure 2.3. This simple octahedral arrangement consists of 8 corners sharing oxygen octahedral forming a cube. A small cation (Ti, Zr) occupying its centre and larger cations (Pb, Ba) filling the interstices between octahedral.

Figure 2.3: Perovskite structure of PZT.

The most commonly available piezoceramics, namely lead zirconate titanate (PZT) comprises a solid solution of PbZrO_3 (53%) and PbTiO_3 (46%). When dealing with piezoelectricity, piezoceramics are transversely isotropic in the plane normal to the poling direction, implying $d_{31} = d_{32} \neq d_{33}$ and $d_{15} = d_{24}$. Mechanically, they are isotropic (Sirohi and Chopra, 2000b).

Being chemically inert, PZT demonstrates competitive characteristics such as light weight, low-cost, small size and good dynamic performance. Besides, it exhibits large range of linearity, fast response, long term stability and high energy conversion efficiency. The PZT patch can be manufactured in any desired shape, size and thickness at relatively low-cost. High elastic modulus (comparable to that of aluminum) renders PZT a good actuator. On the other hand, high strain coefficients also ensure good sensing capability. PZT is thus an ideal material to be used as collocated actuator and sensor.

However, inherent deficiencies such as being fragile, brittle and having low tensile strength sometimes limit its application. Ensuing problems caused by the abovementioned deficiencies include inability to withstand bending and poor conformity to curved surface. Considerable fluctuations of electrical properties with temperature also pose difficulties when it is used under environment with unstable ambient temperature.

2.6.4.2 Piezopolymers

Polyvinylidene Fluoride (PVDF) is the most frequently used piezopolymer. As the name implied, it is a polymer made up of long chains of repeating monomer ($-\text{CH}_2-\text{CF}_2-$). High dipole moment of this polymer results in stronger piezoelectric effect than the other organic materials.

PVDF film is manufactured by solidification from its molten phase, which is then stretched in a particular direction and poled. PVDF is characterized by its lightness and transparency. Ease of shaping and formation into thin sheets as well as flexibility allow the PVDF films to be customized to fit the intended application such as adhering to curved surfaces. Low stiffness (Young's modulus is $1/12\text{th}$ that of aluminum) of PVDF ensures negligible stiffening effect when attached to the host structure. PVDF is more suitable for sensor applications when compared to piezoceramics despite its relatively lower piezoelectric

coefficients. Table 2.1 lists the typical properties of piezoceramics and piezopolymers (Ghandi and Thompson, 1992).

Table 2.1: Typical properties of PVDF and PZT (Ghandi and Thompson, 1992).

Properties	Units	PVDF	PZT
Density	$(10^3) \text{ kg/m}^3$	1.78	5.7
Relative permittivity, ϵ/ϵ_0	--	12	1700
Piezoelectric constant, d_{31} constant	$(10^{-12}) \text{ m/V}$	23	78
Piezoelectric voltage constant, g_{31} constant	$(10^{-3}) \text{ Vm/N}$	216	5
Coupling factor, k_{31} constant	% @ 1 kHz	12	21

A broad range of properties, sizes and shapes are readily available in the industry (PI Ceramic, 2006) for both types of piezoelectric materials. When employed as smart materials in SHM, thin sheet of piezoelectric material is preferred to prevent intervention to the integrity of the host structure.

2.6.5 Secondary effect

The linear constitutive equations (Equation 2.9 and Equation 2.10) are generally valid under low electric fields. Under high externally applied electric field, non-linearity comes into picture due to the effect of electrostriction, which can be accounted for with an additional term in the equation. The electrostrictive effect is independent of the direction of the electric field (Sirohi and Chopra, 2000a).

In the case of piezoceramics, the non-linearity effect may be complicated by the aging effect as the properties of the ceramics decay logarithmically with time. Therefore, the validity of the piezoelectric strain coefficient should be investigated periodically, especially when the materials have been exposed to elevated temperatures.

2.6.6 Practical considerations

2.6.6.1 Depoling

Throughout the service life of the piezoelectric materials, the working temperature should be well below Curie temperature, typically varies from 150°C to 350°C for most of the PZT crystals. On the other hand, an excessive strong field (greater than 80% of the rated coercive field, $> 12 \text{ kV/cm}$), opposite to the poling direction should be prevented as it will cause the dipoles to be shifted away from the original direction. Depoling during the service life will result in loss of piezoelectricity and renders the material unusable.

2.6.6.2 Hysteresis

Magnitude of hysteresis is closely related to the applied electric field (Littlefield, 2000). The presence of hysteresis may be significant in some area of applications such as the active control schemes for smart structures and micro-positioning. These devices rely heavily on the direct strain induced by the piezoceramic actuators.

When employed as piezo-impedance transducers in SHM and system identification using the EMI technique, the effect of hysteresis is usually negligible as the applied electric field is small.

2.7 Application of EMI Technique in SHM

The transduction capability of piezoelectric material has been adopted for applications in various fields. Piezoceramics such as PZT possesses good actuating and sensing capability. This special feature of PZT acting as a collocated actuator and sensor has recently been employed for NDE in the field of SHM.

The EMI technique, which emerged about a decade ago, employs piezo-impedance transducers (normally PZT patches) to dynamically actuate the host structure and simultaneously sense its responses. Damage in the structure will be reflected from its change in structural response. Changes in the structural vibrational response will in turn be sensed by the piezo-impedance transducer. The underlying physical principles of the EMI technique are discussed in the ensuing section.

Another novel technique, commonly known as wave propagation technique, also employs PZT patches in damage detection (Ihn and Chang 2004a). In this technique, built-in PZT patches are used as transmitters and receivers to generate diagnostic stress waves along the host structures. Structural damage can be detected from changes in the received signal. This technique is proven to be effective in detecting debonding or delamination in composites and fatigue crack growth (Ihn and Chang 2004b).

Giurgiutiu et al. (2004) proved the feasibility of concurrent applications of the EMI technique and the wave propagation technique by employing the same PZT patch attached on an aircraft structure. The EMI technique is sensitive in detecting the presence of damage whereas the wave propagation technique is capable of locating the damage. In this study, focus has been placed on investigating the applications of the EMI technique employing surface bonded PZT patches.

2.7.1 Physical principles of EMI technique

The EMI technique shares similar working principles as the conventional local dynamic response techniques described in previous section. However, the frequency range employed in the EMI technique (30 - 400 kHz) is much higher. The method of interrogation also differs from each other.

The mechanically attached (surface-bonded or embedded) PZT patch is dynamically excited by an alternating voltage, sourced by an impedance analyzer, uniformly across the patch. The vibrationing force generated by the PZT patch can then be transferred to the host structure. The corresponding structural response at different excitation frequency will modulate the electric current across the PZT patch.

The modulated current, in terms of complex electrical admittance (conductance and susceptance signatures) is also measured and recorded by the impedance analyzer. This frequency response function can be graphically plotted, which yields a spectrum that serves as an indication to the structural response. Any subsequent damage or interference on the structure, which causes a change in structural response, can be reflected qualitatively from the alteration in the spectrum as exemplified in Figure 2.4.

Figure 2.4: Typical plot of admittance signature against frequency for an aluminum beam under different health conditions in frequency range of 57 – 59 kHz.

Comparing the different stages of the plot, it could be observed that the progressive leftward shift in resonance peak (reduction in modal frequency) could serve as an indication of the existence of damage. This agrees well with the structural dynamic theory stating that occurrence of damage would reduce the overall structural stiffness which is reflected through the reduction in modal frequency. Bhalla and Soh (2003) reported the feasibility of diagnosing blast/seismic induced damages using the EMI technique. Naidu and Bhalla (2002) showed the robustness of the EMI technique in characterizing damages induced in concrete structure. Park et al. (2000) demonstrated the applicability of the EMI technique in lab-size civil structures such as RC wall, steel bridge and pipe joint. Ayres et al. (1998) studied qualitatively the feasibility of employing the EMI technique on a quarter-scale deck truss bridge joint. In general, the local damage detection capability of the EMI technique has been well accepted.

2.7.2 Wave propagation

The actuation of a surface-bonded PZT patch generates propagating waves, mainly surface waves such as Rayleigh waves. The waves travel radially outwards on the plane at which the PZT patch is attached. Therefore, damage detection capability of a surface-bonded

PZT patch is stronger in the parallel plane than those occurring in the thickness direction.

2.7.3 Damage detection and characterization using EMI technique

Application of the EMI technique employing piezoceramics in the field of SHM was proposed by Chaudhry et al. (1994) and Sun et al. (1995). The initial attempt was focused on the use of raw electrical admittance signatures. Damage detection and characterization were achieved through statistical quantifiers. These statistical approaches are non-parametric (Winston et al., 2001) in nature, as quantification of damages is based on the measured electrical admittance instead of the physical parameters related to the structural response. Root mean square deviation (RMSD), signature assurance criteria (SAC), waveform chain code (WCC) and adaptive template machining (ATM) are among the non-parametric quantification approaches reported in the literature. RMSD appears to be one of the most robust approaches (Giurgiutiu and Rogers 1998):

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{i=N} (w_i - u_i)^2}{\sum_{i=1}^{i=N} u_i^2}} \times 100 \quad (2.17)$$

where u_i is the reference signature obtained from the intact structure (baseline) and w_i is the signature acquired from the structure after certain damage or structural changes, where i is the reference signature at particular frequencies.

Pros and cons exist in the non-parametric approaches. Advantages can be seen from the fact that no information regarding the structure is required in advance. Modeling is also not required which greatly simplifies the application. However, physical changes in the host structure remain unknown and its corresponding structural parameters can hardly be derived. This causes extreme difficulty for the damage mode identification and damage severity quantification.

Bhalla (2004) and Lim et al. (2006) attempted some parametric based damage detection using equivalent structural parameters in characterizing the severity of damage in a structure.

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The approach shows considerable advantages over the conventional non-parametric approaches. Xu et al. (2004) successfully attempted damage quantification (limited to one hole) using the EMI technique with evolutionary programming.

2.7.4 Practical considerations related to application of EMI technique in SHM of civil structures

Despite many experimental works conducted throughout the years on realizing the EMI technique, real life and large scale commercial application in the field of civil engineering remains at its embryonic stage due to lack of thorough understanding into various practical issues and constraints. Issues such as long term consistency of measured admittance signatures, durability of PZT patch under harsh environmental conditions, appropriate protection, performance and efficiency of the technique with different bonding conditions, fragility, reliability of damage identification and quantification method, installation procedures, economy of application, monitoring, analysis and maintenance guidelines are pending more studies and standardization. Some of them are discussed in the following sections.

2.7.4.1 Frequency range selection

One of the unique characteristics of the EMI technique is its high frequency of excitation (in the order of kHz) which ensures high sensitivity in sensing. This enables the detection of incipient crack invisible to naked eyes (Bhalla, 2001).

According to the recommendation by Sun et al. (1995), in the application of the EMI technique, major vibration modes of structure should be included and the frequency range with high mode density (large number of resonance peaks) is preferred. Park et al. (2003) additionally recommended that the frequency range should be kept within 30 kHz to 400 kHz to ensure high sensitivity to incipient damage. They further recommended that frequency larger than 500 kHz is unfavorable if lateral modes are used because the sensing region becomes extremely localized and the PZT patch shows adverse sensitivity to their bonding

conditions. At extremely high frequency, the sensing range becomes very limited and the resonance of the PZT patch dominates that of the structure, thus rendering the outcome of sensing ambiguous and inefficient. However, this limitation does not exist when the thickness modes are utilized and the excitation could go up to MHz (Park et al., 2005).

2.7.4.2 Excitation voltage and signature acquisition

The PZT patch is normally excited by the impedance analyzer with an alternating voltage signal of 1 volt r.m.s. (root mean square) over the user specified frequency range. The magnitude and phase of the corresponding steady state, modulated current are directly recorded in the form of complex admittance (conductance and susceptance) signatures in the frequency domain, thereby eliminating the requirements of intensive domain transforms (Bhalla, 2004).

Sun et al. (1995) reported that the conductance signature remained practically constant when the excitation voltage was increased from $0.5V$ to $15V$, and concluded that the excitation level does not affect the conductance signature. They further suggested that higher excitation voltage could improve the signal to noise ratio, which could correspondingly improve the ability to identify weak modes.

2.7.4.3 Sensing range and optimal placement of PZT patch

High frequency of excitation induced by the PZT patch renders the actuation and sensing zone on the host structure to be localized. The sensing zone is also closely related to the host materials, ranging from $0.6m$ in concrete to $2 - 3m$ in metal (Esteban, 1996). It is also affected by the structure's geometry, the frequency of excitation and the presence of structural discontinuities.

Therefore, in actual application, spacing between the PZT patches should be reasonably chosen according to the abovementioned considerations. Up to date, no systematic guidelines or established theories are available to estimate the sensing zone and optimal placement of the PZT patches in a complex structure. This is mainly attributed to the complexities involved in

modeling the energy dissipation at such high frequency. Soh and Bhalla (2000) suggested that the PZT patches should be placed at critical location such as those susceptible to shear crack and bending failure. The number of PZT patches required in monitoring the entire structure can be optimized if they are located wisely.

2.7.5 Long term performance of PZT patch

Consistency and reliability of the EMI technique under various environmental conditions are two of the more critical issues in actual application. Repeatability of signatures acquired from the PZT patch should be reasonably high if the structure remains intact throughout the period of monitoring. The technique should be functional and sustainable under various environmental conditions.

This is especially important in the field of civil engineering where the patches (surface bonded on structure) are exposed to dirt, fluctuations of humidity and temperature, frost, and other severe conditions. Durability of the patch in terms of perseverance of the piezoelectric properties and resistance to wear and tear should be satisfactory. Up to date, very little work has been done in this area (Bhalla, 2004). Investigation into appropriate protection for surface-bonded PZT patch is also crucial. Embedding the PZT patch (Annamdas, 2004) may be a viable alternative to protect the patch. However, the vulnerable PZT patch could easily fail during the process of concrete casting. Embedment also renders replacement and maintenance of the transducer impossible.

2.7.6 Effect of temperature

The electrical admittance signatures acquired from the impedance analyzer are temperature sensitive (Sun et al., 1995; Park et al., 1999). The undesirable effects caused by temperature on the acquired signatures are the horizontal shift, due to changes in the host material's stiffness, and the vertical shift, due to variations in parameters ϵ_{33} and d_{31} of the PZT patch (Bhalla, 2004).

Bhalla (2001) conducted some numerical simulations using finite element method (FEM)

to study the effect of temperature on the admittance signature caused by changes in the PZT patch's or host structural properties. Influence of temperature on bonding layer, actuation capability and physical properties of PZT patch were investigated by Nguyen et al. (2004) and Schulz et al. (2003). Fortunately, all researchers concluded that the overall shift in the frequency spectrum varies linearly with temperature over narrow frequency bands. The most critical vertical shift was caused by the changes of ε_{33} .

In real situation, it is therefore essential to differentiate the effects between damage and temperature, as the actual working condition is generally subjected to considerable temperature fluctuations. This necessitates the development of a compensation algorithm to decouple the two. Sun et al. (1995) observed that over a small frequency range, the overall effect of temperature comprises of a superposition of uniform horizontal and vertical translations of the signature. This phenomenon has distinct difference from the abrupt and localized variation in signature caused by damages. Sun et al. (1995) suggested a compensation technique based on cross correlation coefficient to compensate for temperature induced horizontal shift. Park et al. (1999) latter proposed an empirical based methodology for temperature compensation, proving the damage detection capability of the EMI technique under fluctuating temperature.

2.7.7 Effect of bonding

For a surface bonded PZT patch, efficiency of strain transfer between the PZT patch and the host structure is closely related to the adhesive layer, mechanically joining the two. Therefore, the performance and behavior of the bonding layer is crucial for an effective strain transfer and thus efficient actuation and sensing. Shear lag effect may be significant for those with thick bonding.

Some researchers disregard the effect of bonding film while applying the EMI technique. Bhalla (2004) suggested that the effect of adhesive on the PZT patch is negligible if the bonding layer is less than one third of the patch's thickness. Impedance based modeling of the EMI technique proposed by Liang et al. (1994) also neglected the bonding layer. Xu and Liu (2003) extended the abovementioned model by assuming the bonding layer as a single degree

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of freedom (SDOF) spring-mass-damper system placed in between the PZT patch and the structure.

In actual application, the effect of bonding layer turns up to be more complicated when external factors such as temperature changes are involved.

Nguyen et al. (2004) studied the actuation efficiency of the PZT patch under varying environmental temperature and adhesive layers. They found that the quality of bonding is affected by the effective working condition such as the ambient temperature and type of bonding. It was also reported that temperature effect on the viscoelasticity of bonding is more pronounced than that on the properties of the host structure. However, frequency range considered in that study is considerably lower than the operational frequency of the EMI technique. Alfredo (2003) investigated the impact of finite stiffness bonding on the sensing effectiveness of piezoelectric patch. He suggested that the shear lag effect and end bonding must be carefully assessed in order to enhance the quality of the sensing output. Ong et al. (2002) studied the effects of adhesive on the electro-mechanical response of a piezoceramic transducer coupled smart system.

2.7.8 Instrumentation and other considerations

One existing shortcoming of the EMI technique in real-life application is the use of the bulky and heavy impedance analyzer. This reduces the agility and mobility of the whole monitoring system.

Besides being not portable, the analyzer such as HP4192A and HP4194A are quite costly as they possess extra functions that are redundant in the application of the EMI technique. Peairs et al. (2004a) developed a miniaturized, portable, operational amplifier-based turnkey device capable of measuring electrical impedance of PZT patch with accuracy comparable to the conventional impedance analyzer. However, this novel device has yet to be commercialized.

In the case of real life monitoring of the entire civil structure, a large number of PZT transducers are expected to be placed at various major structural elements. Corresponding large numbers of wires could pose inconveniences, for instance, unduly long monitoring time,

enormous number of data for analysis, difficulty in handling the wires during installations etc. Multiplexing of the PZT patches could be a solution to the problem. Some successful applications on multiplexing had been attempted by Bhalla (2004). However, the technique is relatively immature when compared to the well established multiplexing of fiber optic strain sensor.

In terms of software, one which is able to control the impedance analyzer for actuating the PZT transducers and acquiring data by the personal computer is essential. The basic software should be written in a way that enables real-time, autonomous data acquisition. Further, advanced software should include autonomous temperature and humidity compensation algorithm and be able to alert the inspector when significant deviation from the healthy state signatures is detected. With existing technology, the abovementioned criteria are attainable. But more research and real-life study ought to be conducted to confirm its workability and reliability.

Another limitation of the EMI technique is its inability to identify the failure modes or nature of damage occurring in the host structure. Also, the exact quantification of damage is extremely difficult. The extent of damage can only be qualitatively recognized through the changes in admittance signatures' spectrum.

When compared to the application of FBG based strain sensor, FBG sensing technology is relatively more mature, especially in real life SHM (Storoy et al., 1997; Lin et al., 2004). Application of the EMI technique on field monitoring of large scale structure is rarely attempted. All the abovementioned practical problems ought to be solved before real life application is possible. Some of the problems are studied and addressed in this research project.

2.8 Modeling of EMI Technique

2.8.1 Analytical model

A number of analytical models have been proposed to simulate the interaction between the piezo-impedance transducer and the host structure. The static equivalent-force (SEF)

modeling approach, first proposed by Crawley and de Luis (1987) assumes a frequency independent PZT-structure interaction. The actuation force from the PZT patch is determined through static equilibrium and strain compatibility. The host structure is simplified into a static stiffness. Despite the convenient simplification in the modeling equation brought about by the omission of the complex terms in the piezoelectric constitutive equations, considerable loss in accuracy is inevitable. This is a result of ignorance on the effect of inertia and damping. In fact, this modeling approach is highly impractical for the EMI technique which adopts high frequency (in the order of tens to hundreds of kHz) of excitation. In depth discussions on SEF model can be found in Lalande (1995), Fairweather (1998) and Littlefield (2000).

Some other modeling approaches are also available in the literature. The energy-based modeling technique proposed by Pan, Hansen and Snyder (1991) investigated the development of a dynamic beam model based on Euler-Bernoulli beam theory. The model prediction shows closer agreement with experimental measurement when compared to those from the SEF model. However, it has been reported that the energy-based technique can be extremely sophisticated when applied to structure such as plates (Fairweather, 1998).

A brilliant impedance based modeling approach was proposed by Liang et al. (1993). This approach simplifies the host structure into a skeletal structure (Figure 2.5a). The PZT patch is assumed to be a vibrating thin bar undergoing axial vibration with its interaction with the structure confined at the driving point, as shown in Figure 2.5(b). Therefore, the entire structure can be represented by its drive point mechanical impedance, Z , resembling a black box (Figure 2.5a). Incorporating the dynamic force equilibrium and PZT constitutive equations, Liang et al. (1994) derived the following expression for the 1-D electro-mechanical admittance.

$$\bar{Y} = 2\omega j \frac{wl}{h} \left[\bar{\epsilon}_{33}^T + \left(\frac{Z_a}{Z + Z_a} \right) d_{31}^2 \bar{Y}_{11}^E \left(\frac{\tan \kappa l}{\kappa l} \right) - d_{31}^2 \bar{Y}_{11}^E \right] \quad (2.18)$$

where ω is the angular frequency of the driving voltage, w , l and h are the width, half length and thickness of the PZT patch respectively, and κ is the wave number. Z_a and Z are the mechanical impedance of the actuator and the structure respectively. According to the impedance based modeling approach, the actuator impedance Z_a is defined as:

$$Z_a = \frac{\kappa w h \bar{Y}_{11}^E}{(j\omega) \tan(\kappa d)} \tag{2.19}$$

Figure 2.5 (a): A generic single degree of freedom electro-mechanical representation of active material with PZT actuator.

Figure 2.5 (b): Idealized 1-D PZT – structure interaction.

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Structural stiffness, actuator stiffness and displacement in static based derivation are replaced by structural impedance, actuator impedance and velocity respectively. Integration of the dynamic PZT patch's impedance and the structural impedance render the 1-D electromechanical coupling equation more comprehensive than the static based equation. Lalande (1995) studied the impedance model as applied to ring and shell structures, which also includes the effect of transverse shear. Detailed description on this method is provided by Cheng and Wang (2001).

It is worth mentioning that the initial derivation of the impedance based modeling method focuses on the simulation of PZT-structure interaction with frequency lower than those employed in the EMI technique, typically less than a few kHz.

Successful applications of the impedance based modeling in the simulation of the PZT-structure interaction at relatively high frequency range (more than 10 kHz) have been reported by Zagrai and Giurgiutiu (2001). In their study which focuses on a thin aluminum plate, reasonable accuracy has been achieved between the analytical result and the experimental outcome. More comparisons of the impedance based analytical models and experiments could be found in the study by Ong (2003).

However, the abovementioned 1-D model is considered oversimplified for the modeling of some more complex structures. Zhou et al. (1995) extended the impedance based 1-D (skeletal) model to a more generic 2-D (planar) model. Direct impedances Z_{xx} and Z_{yy} , and the cross impedances Z_{xy} and Z_{yx} are incorporated in the equation:

$$\bar{Y} = 4j\omega \frac{wl}{h} \left[\frac{\bar{\epsilon}_{33}^T}{(1-\nu)} - \frac{2d_{31}^2 \bar{Y}^E}{(1-\nu)} + \frac{d_{31}^2 \bar{Y}^E}{(1-\nu)} \left\{ \frac{\sin \kappa l}{l} \quad \frac{\sin \kappa w}{w} \right\} N^{-1} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \right] \quad (2.20)$$

where ν is the Poisson ratio, w is half width of the PZT patch, $\kappa = \omega \sqrt{\frac{\rho(1-\nu^2)}{\bar{Y}^E}}$ indicating the 2-D wave number (ρ is the density of the PZT patch) and N is a 2 x 2 matrix, given by

$$N = \begin{bmatrix} \kappa \cos(\kappa l) \left\{ 1 - \nu \frac{w}{l} \frac{Z_{xy}}{Z_{axx}} + \frac{Z_{xx}}{Z_{axx}} \right\} & \kappa \cos(\kappa w) \left\{ \frac{l}{w} \frac{Z_{yx}}{Z_{ayy}} - \nu \frac{Z_{yy}}{Z_{ayy}} \right\} \\ \kappa \cos(\kappa l) \left\{ \frac{w}{l} \frac{Z_{xy}}{Z_{axx}} - \nu \frac{Z_{xx}}{Z_{axx}} \right\} & \kappa \cos(\kappa w) \left\{ 1 - \nu \frac{l}{w} \frac{Z_{yx}}{Z_{ayy}} + \frac{Z_{yy}}{Z_{ayy}} \right\} \end{bmatrix} \quad (2.21)$$

Z_{axx} and Z_{ayy} are the two components of the mechanical impedance of the PZT patch in the two principal directions, derived in a similar manner as for the 1-D impedance based model.

However, this model possesses 4 impedance parameters which has altogether 8 unknowns but only 2 equations. The large number of unknowns renders the system of equations highly indeterminate and thus inapplicable.

On the other hand, it should be noted that the additional factors of 2 and 4 are introduced respectively to Equations 2.18 and 2.20 when compared to the original derivations of Liang et al. (1994) and Zhou et al. (1995) due to the fact that only one-half and one-fourth of the patch are modeled in these initial derivations.

The shortcoming of the above 2-D equation is recently overcome by Bhalla and Soh (2004a and 2004b) who introduced the concept of “effective impedance”. It was suggested that the actual interaction between the patch and the structure is not restricted at the end points but extended all over the finite size of the PZT patch. They introduced the concept of effective velocity rather than drive point velocity, thus ensuring the force transmission between the PZT patch and the structure occurs along the entire boundary of the patch. The effective displacement is also redefined as change in area divided by undeformed perimeter length. This approach overcame the problem of unsolvable unknowns as there is only one complex term, effective host structural impedance $Z_{s,eff}$ involved in the equation:

$$\bar{Y} = 4\omega j \frac{l^2}{h} \left[\frac{\bar{\epsilon}_{33}^T}{(1-\nu)} - \frac{2d_{31}^2 \bar{Y}^E}{(1-\nu)} + \frac{2d_{31}^2 \bar{Y}^E}{(1-\nu)} \left(\frac{Z_{a,eff}}{Z_{s,eff} + Z_{a,eff}} \right) \left(\frac{\tan \kappa l}{\kappa l} \right) \right] \quad (2.22)$$

where $Z_{a,eff}$ is the effective actuator's impedance.

Bhalla (2004) showed experimentally that the effective impedance based model produced higher accuracy than the 1-D model (Liang et al., 1994).

2.8.2 Numerical model

Despite the ability of analytical model to simulate the PZT-structure interaction, the method is limited to simple structures which have regular shapes. When the structure to be studied is relatively complex or with sophisticated boundary conditions, or when the targeted model involves a system of structures interacting with each other, analytical modeling is usually impossible.

Numerical model turns up to be a viable option, which often provides close approximation to the exact solution. The outcome is usually satisfactory for engineering applications. Recent development of FEM software as well as the rapid advancement in computer hardware renders the numerical modeling technique more robust. Currently, the FEM finds a wide range of applications in the engineering community. Lalande (1995) summarized three approaches of FEM based modeling of the dynamic PZT-structure interaction, namely direct formulation of element for specific applications, thermo-elastic analogy and use of commercial FEM codes. All these models incorporate the piezo-transducer in the simulation.

Fairweather (1998) proposed a semi analytical modeling approach incorporating the FE model and the impedance based model, commonly known as FEA-based impedance model. This model enables the modeling of PZT-structure interaction without the presence of PZT patch in the model, as it has been simplified and represented by a force or moment. This approach retains the simplicity of the impedance based model while utilizes the robustness of FEM including the ability in modeling of generic distributed structures possessing anisotropic material, mass loading and non-uniform boundary conditions.

Bhalla (2001) and Lim (2004) extended the FEA-based impedance model to the frequency range commonly used in the EMI technique. Bhalla (2001) attempted the use of FEM to simulate the damage in concrete by assuming the experimental stress-strain curve to follow the Drucker-Prager plasticity model. Bhalla (2004) also attempted with the 2-D

effective impedance model.

Despite the advantages discussed above, the FEM possesses some inherent shortcomings such as its solution removes the physical insight that can be obtained with analytical solution process. Besides, a new solution is always required for each adjustment made, which causes the process of analysis time consuming and expensive.

2.9 Prospect of Integrated Use of Smart Materials in SHM

Smart materials often possess unique characteristics or behavior, when wisely utilized; appear to be smart in certain applications. However, they carry inherent limitations, which are sometimes insurmountable. For instance, optical fiber can only act as a passive sensor, it cannot produce actuation. SMA on the other hand, can only actuate and piezoceramics is fragile to be handled. These limitations could hinder the development of an efficient smart structures and systems. It is conceived that if the strengths of each smart materials are utilized to complement the shortcomings of others, a more robust intelligent system can be developed

In the field of SHM, Peairs et al. (2004b) investigated the feasibility of a self-sensing and self-repairing bolted joints. In that study, piezoelectric transducer was used for sensing of loosened bolt while SMA was adopted as actuator to restore the tension of the loose bolt.

Various studies have proven the ability of the FBG sensor in measuring strain of attached structure. On the other hand, piezo-transducer is also found to be useful in damage detection. Incorporation of both smart materials is expected to complement the shortcomings of each other and thus forming a more comprehensive structural health monitoring system.

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3.1 Introduction

Despite the advantages of the EMI technique discussed in the previous chapter, this technique is relatively immature in real-life application, especially when compared to other smart materials such as optical fiber sensors. Lack of in depth, experimental study is one of the major reasons as reflected from the limited publications related to this topic in the literatures. Some of the existing limitations pending to be solved are briefly elucidated in the following paragraph.

Firstly, the inherent limitations of the material itself, such as the brittleness of the piezoceramics renders handling and installation very difficult, the dependency of PZT patch's properties to ambient conditions including fluctuations in temperature (Nguyen et al., 2004) and humidity (Bhalla, 2004), and susceptibility to electrical interference pose problems to actual application. Secondly, the technique is currently lacking of systematic monitoring procedures or guidelines as well as reliable data processing tool. Thirdly, the inability of the EMI technique to identify failure or damage mode and quantify damage in the host structure hinders its usage considerably. Other practical considerations such as the effect of bonding layer (Xu and Liu, 2003), durability during service life under harsh environmental conditions, reliability of long term monitoring, suitable instrumentation (Peairs et al., 2004a) and cost effectiveness also deserve deeper investigation. All these issues contribute to the difficulties that ought to be resolved before real life and large scale application of the EMI technique is possible.

This chapter presents the investigations into the long term repeatability of the admittance signatures acquired from the PZT patch under various environmental conditions. Protections of the PZT patch from wear and tear and environmental attack are also studied.

3.2 Consistency of Admittance Signatures Acquired from PZT Patch

Monitoring of structural health using the EMI technique depends heavily on the electrical admittance signatures acquired at different frequency range. The signatures, on the other hand, are affected by the PZT patch, the bonding film and the host structure. Vibrating at high frequency, slight degradation in one of the parties is expected to affect the signatures substantially. In real-life application, the consistency or long term repeatability of the signatures under harsh environment such as in the construction site ought to be carefully investigated to confirm its reliability.

Under normal working condition, the consistency of piezoelectric properties is relatively high. Aging rates of some typical piezoceramics are summarized in Table 3.1. It could be seen that the aging rate of the key piezoceramics’ properties are generally lower than 5% per decade. PI Ceramic (2006) reported that the lifetime of a piezoelectric is not limited by wear and tear as they are specifically designed for high duty cycle applications. Endurance test conducted (PI Ceramic, 2006) on piezoelectric actuator showed that the material performs consistently even after several billion of cycles. Therefore, it could be inferred that the deterioration of the PZT patch itself is not a major concern under normal use. However, this may not be true when the patch is surface-bonded on civil structure which is constantly exposed to harsh environment.

Table 3.1: Aging stability (relative change of the parameters in % per decade) of typical piezoceramics (PI Ceramic, 2006).

Types of PZT	PIC 110	PIC 140	PIC 181	PIC 151	PIC 155	PIC 255
Aging rate of relative dielectric constant, C_k	-8.5	-1.0	-1.0	-2.0	-2.0	-1.0
Aging rate of coupling factor, C_ϵ	-5.0	-4.0	-0.25	-4.0	-3.0	-2.5

The following section elucidates a series of experimental studies conducted to investigate the consistency of signatures acquired under different environmental conditions. The effects of bonding and temperature are excluded here, but presented in the following chapter.

3.3 Experimental Setup and Procedures

3.3.1 Specimens' preparation

6 different lab-size samples, surface bonded or embedded with PZT patches as shown in Figure 3.1 were prepared in this experiment. According to the nature of host materials, the specimens could be classified into three categories, namely aluminum, concrete and rock. The PZT patches adopted in this study were PIC 151, a modified lead zirconate titanate (PZT) ceramic with high permittivity, coupling factor and charge constant (PI Ceramic, 2006). Its material properties are listed in Table 3.2. Adhesive used for bonding was two parts, high strength epoxy, RS 159-3957 (RS Components, 2006). Dimensions of the specimens and the PZT patches are shown in Figure 3.1 and Table 3.3 respectively.

The admittance signatures of the PZT patches were monitored at certain time interval for a period of one year. A summary on details of each sample, including the host structures, sizes of patches, exposed environmental conditions and types of protection assigned are tabulated in Table 3.3.

Three aluminum beam specimens, each surface-bonded with four PZT patches were placed under different environments. Only three of the patches are discussed here. The extra patches in each specimen were bonded as a reserve in case of failure. Specimens B1, B2 and B3 were identical. Both specimens B1 and B2 were placed outdoor. Specimen B1 was exposed while specimen B2 was buried under clayey soil (placed inside a bucket). These two samples were however prevented from direct exposure to sunlight and rain. The samples may be in contact with water only during heavy rain. This is an attempt to simulate the situation of nominal construction site or in service civil structures.

This is justifiable as in normal application, the PZT transducer is expected to be reasonably protected. Situation of extreme harsh environment is not considered in this study. Specimen B3 was placed inside the laboratory (room condition). The main objective of this set of specimens is to investigate the durability of the patches and repeatability of the acquired signatures under repeated cycles of fluctuating temperature and humidity, under the typical tropical climate, such as in Singapore.

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Figure 3.1: Specimens of different materials attached with PZT patches.

- (a) Aluminum beam (identical configurations in all specimens: B1, B2 & B3)
- (b) Concrete block (C1, C2)
- (c) Cylindrical rock (R)

Table 3.2: Material properties of PIC 151 (PI Ceramic, 2006).

Properties	Units	Symbols	Values
Density	kg/m^3	ρ	7800
Curie temperature	$^{\circ}C$	T	250
Relative permittivity	--	$\epsilon_{33}^T / \epsilon_0$	2400
	--	$\epsilon_{11}^T / \epsilon_0$	1980
Dielectric loss	--	$\tan \delta$	0.015
Coupling factors	--	k_p	0.62
	--	k_{33}	0.69
	--	k_{31}	0.34
Charge constant	$\times 10^{-12} / mV$	d_{31}	-210
		d_{33}	450
		d_{15}	580
Elastic constant	$\times 10^{-12} m^2 / N$	s_{11}^E	15
		s_{33}^E	19
Aging rate	% per decade	C_f	0.2
		C_k	-2
		C_{ϵ}	-4

In this study, 2 types of protections were attempted. For surface bonded PZT patch, a layer of silicone rubber was applied across the patch, covering a small portion of the host structure surrounding the patch. On the other hand, some patches were protected through embedding them in concrete.

Bhalla (2004) suggested the use of silicone rubber to protect the PZT patches from humidity as well as wear and tear. He also confirmed the damage detection capability of the

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EMI technique subjected to high humidity when the PZT patch was covered with commercially available silicone rubber. In this study, recommendation by Bhalla (2004) was adopted. However, it was found that more than one type of silicone rubbers is available in the market. In this study, two types of silicone rubbers, herein indicated as silicone rubber A (Hi-Bond, 2006) and silicone rubber B (Dow Corning, 2006) were adopted. Silicone rubber A, normally used as glass sealant, is much cheaper than silicone rubber B. In this study, the silicone rubber was applied as one thin layer (Figure 3.1). More layers could be applied for better protection.

Two concrete specimens, namely C1 and C2 were prepared with one PZT patch embedded inside each specimen. Past experience suggests that direct placement of the patch into concrete without protection during casting and mixing can hardly be achieved due to the high probability of breaking the patch. Moreover, direct contact with wet and corrosive concrete may affect the properties of PZT patch. The author had previously attempted to use a layer of silicone rubber to protect the patch before placement but it was later discovered that the damping effect caused by the layer of silicone rubber on the PZT patch is too large, rendering its actuation highly inefficient. Therefore, a novel technique proposed by Annamdas (2004) was adopted to protect the PZT patch in which the patch was wrapped with a layer of epoxy (much stiffer than silicone rubber and thus better strain transfer) before embedding in concrete. The two concrete specimens were then placed under outdoor and indoor conditions, respectively (Table 3.3).

Two PZT patches were surface-bonded on a cylindrical rock sample (granite), herein denoted as R. They were protected with two different grades of silicone rubber as described earlier. This aimed at investigating the applicability of the EMI technique on rock.

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Table 3.3: Details of specimens for consistency test.

Host structure	Specimens label	No. of patches	Patch label	Patch size (mm)	Protections	Environmental conditions
Aluminum beam	B1	3	1	10x10x0.2	Silicone rubber A	Outdoor
			2	10x10x0.2	Silicone rubber B	
			A	10x10x0.5	Unprotected	
	B2	3	3	10x10x0.2	Silicone rubber A	Outdoor (Buried under dry soil)
			4	10x10x0.2	Silicone rubber B	
			C	10x10x0.5	Unprotected	
	B3	3	5	10x10x0.2	Silicone rubber A	Indoor
			6	10x10x0.2	Silicone rubber B	
			E	10x10x0.5	Unprotected	
Cylindrical Rock	R	2	7	10x10x0.5	Silicone rubber A	Outdoor
			8	10x10x0.2	Silicone rubber B	
Concrete block	C1	1	9	10x10x0.2	Wrapped with hardened epoxy and embedded into concrete	Indoor
	C2	1	10	10x10x0.5		Outdoor

3.3.2 Experimental setup and considerations

Figure 3.2: Pictorial illustration of experimental setup for EMI technique.

Experimental setup for the EMI technique used in this study is depicted in Figure 3.2. The HP 4192A impedance analyzer (Hewlett Packard, 1996) played a key role in the EMI technique. It applied a $1V$ (*rms*) A.C. of predetermined frequency range across the PZT patch and measured the corresponding modulated current. The resulting output, in terms of electrical admittance, consisting of conductance (real component) and susceptance (imaginary component) was recorded by a personal computer. A 3499B multiplexer module (Agilent Technologies, 2003) served as an interface between the analyzer and the PZT patch. It allowed a convenient connection between the impedance analyzer and the personal computer. It is especially useful when large number of PZT patches were switched among each other or multiplexed. More details on the PZT patch preparation, instrument calibration and setup can be found in Bhalla (2001) and Lim (2004).

Throughout the period of monitoring, the admittance signatures were initially acquired at closer interval, starting from once in a few days to each week. Signature acquisition thereafter was conducted only at monthly or quarterly interval when the consistency was confirmed to be sufficiently high.

Despite some of the specimens were placed under different environmental conditions;

they were returned to the laboratory a few hours before the signatures from the PZT patches were acquired, in order to eliminate the effect of temperature and humidity.

During the signature acquisition process, the temperature fluctuation in the laboratory was controlled to be within 24°C to 26°C . Within this range, the fluctuation would have negligible adverse effect on the signatures. The humidity inside the lab was assumed to be practically constant throughout the period of monitoring. Under this context, the effects of temperature and humidity were conveniently eliminated. Any subsequent deviations in the signatures were inferred to be attributed to degradation in the PZT patch or the adhesive layer (the host structure was assumed to be sufficiently robust and remained intact throughout the test).

For specimen B2 (aluminum beam), signatures were recorded with the specimen remained buried in the soil to avoid unnecessary disturbance, which may affect the boundary condition.

Sun et al. (1995) suggested that the conductance signatures are more sensitive to damage detection. Bhalla (2004) however, showed that the susceptance signatures are equally useful if the passive components of the signatures are filtered off. For the sake of simplicity, only the conductance signatures were adopted for comparison in this study.

3.3.3 Results and discussions

Two methods, commonly used for damage detection in the EMI technique, were adopted in examining the repeatability of signatures. The simplest and most straightforward method is by qualitatively observing the admittance against frequency spectrum. Figure 3.3 to Figure 3.6 depict the plots of admittance signatures against frequency ranging from 10 to 100 kHz for the different PZT patches. Another method adopted is the well-accepted damage detection and characterization approach in the EMI technique – RMSD statistical quantifier. In this study, frequency range between 10 kHz to 100 kHz was selected for the RMSD evaluation. A summary of RMSD calculated for all patches is tabulated in Table 3.4. The baseline signatures for all specimens were the first to be acquired.

However, it should be noted that a narrower bandwidth of $35 - 50\text{ kHz}$ was selected for

both concrete specimens, C1 and C2. This is due to the fact that after the sample was cast, acquisition of signatures started before the concrete was fully cured. Therefore, significant curing occurred throughout the period of monitoring resulted in significant variations in the signatures acquired. Thus, frequency range was selected based on observation from the conductance against frequency plot whereby range where an obvious resonance peak occurred was selected. It should also be noted that RMSD is a relative measurement. The value may vary for different frequency range and among different specimens. Appropriate engineering judgment is required to obtain useful information from the numbers. In this case, a wider frequency range was adopted for the evaluation of the RMSD in order to obtain a more representative result. Outcome of the monitoring on each sample is presented and discussed in the following sections

3.3.3.1 Specimen B1 (outdoor)

A glance through Figure 3.3 suggests that the conductance signatures remained virtually unchanged throughout the monitoring period for all three patches in spite of different level of protections. Comparing their RMSD at different period of time (Table 3.4); all values are well within 5%, with the unprotected patch slightly higher than the protected ones. The RMSD values fluctuate faintly throughout the period of monitoring but show no increasing trend against time. Minor fluctuation in RMSD value may be attributed to slight variation in humidity and temperature as well as possible minor inconsistency during the calibration of the impedance analyzer. Higher fluctuation in the unprotected patch can be due to some degradation on the bonding film as the adhesive was unprotected.

Absence of variation in modal frequency (no horizontal shift in resonance peaks) indicates no sign of structural deterioration. This shows that the repeatability of signatures is sufficiently high and thus proving the feasibility of adopting the EMI technique for long term health monitoring of structure under outdoor condition, even with the patch left totally unprotected.

However, an initially unforeseen problem arose in the unprotected patch (patch 1) as one of the wires soldered onto its terminal was jerked off due to wear and tear after 6 months. Monitoring of this sample was forced to be terminated on the tenth month when it was spoiled by some mischievous passerby who plucked out all the wires and caused damages on the

patches' terminals. This happened to all other samples placed outdoor. However, the specimens placed in the lab remained intact and functional till the time this thesis was written.

Figure 3.3: Conductance signatures against frequency plot for specimen B1 (10 – 100 kHz).
(a) Patch A (unprotected)
(b) Patch 1 (protected with silicone rubber A)
(c) Patch 2 (protected with silicone rubber B)

Table 3.4: RMSD values (%) calculated from admittance signatures (10 – 100 kHz) at different stages in comparison to baseline signatures.

Specimen B1 (Outdoor)				
		Patch 1	Patch 2	Patch A
RMSD (%)	1 month	3.41	1.93	3.03
	2 months	3.29	2.99	6.30
	3 months	3.33	3.25	4.39
	4 months	3.84	3.12	3.82
	6 months	4.54	3.55	8.94
	8 months	4.90	4.82	--
	Average	3.89	3.28	4.38
Specimen B2 (Soil)				
		Patch 3	Patch 4	Patch C
RMSD (%)	1 month	7.45	8.15	16.91
	2 months	7.93	8.97	17.94
	3 months	11.20	13.52	23.62
	4 months	7.03	8.01	18.69
	Average	8.40	9.66	19.29

Specimen B3 (Indoor)				
Patch label		Patch 5	Patch 6	Patch E
RMSD (%)	1 month	2.19	2.05	3.28
	2 months	2.06	2.05	3.75
	3 months	3.65	3.04	5.65
	4 months	1.38	1.46	2.12
	6 months	2.32	2.13	2.81
	8 months	3.71	2.88	4.20
	11 months	3.06	4.29	4.32
	15 months	3.30	2.81	4.86
	Average	2.71	2.59	3.88
Specimen R				
		Patch 7	Patch 8	
RMSD (%)	1 month	6.21	9.96	
	2 months	11.39	6.39	
	3 months	12.19	11.11	
	4 months	9.09	11.77	
	6 months	14.50	7.86	
	8 months	19.70	5.83	
Specimen C				
		Patch 9		
RMSD (%)	1 month	30.12*		
	2 months	34.95*		
	3 months	38.11*		
	4 months	39.50*		
	6 months	41.10*		
	8 months	48.09*		
	11 months	46.31*		
	15 months	49.17*		

*Note: Frequency range selected: 35 – 50 kHz

3.3.3.2 Specimen B2 (buried under dry soil)

For the specimen buried under soil, visible fluctuations in admittance signatures throughout the monitoring period can be observed from Figure 3.4. Visually, signatures from all three patches suffered similar amount of disturbances. The average RMSD values throughout the four months computed for patch protected with silicone rubber B, silicone rubber A and unprotected patch are 8.40%, 9.66% and 19.29% respectively. This proved that

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silicone layer, especially silicone rubber B, which is the more expensive one, provided better protection to the patches.

Reason of variations was predicted to be the gradual loss of humidity in the soil especially during the first 2 months (the specimen was buried in soil contained in a bucket which originally contained some moisture). In addition, alteration in boundary condition caused by settlement could be another factor. The monitoring was again forced to terminate when the sample was removed and the soil thrown away by unknown disturber. The boundary condition was thus significantly disturbed and the soil being used was lost. Through this experiment, it was found that human interference ought to be taken into consideration. More robust protection is mandatory for the PZT patches.

Surprisingly, the PZT patches, including the unprotected patch (patch 4) showed virtually no sign of degradation despite being placed under such harsh condition for months. From damage detection point of view, no obvious leftward shift in resonance peaks showed that the structure was undamaged despite the relatively higher RMSD values. More study should be conducted to understand its relationship with humidity and with different type of soil.

This experiment implicitly exposed the weakness of RMSD approach, which may not be a suitable quantifier to characterize damage for long term monitoring. The RMSD approach calculates the relative vertical difference between two signatures at all frequencies. However, damage on host structure is mainly reflected through horizontal shift in resonance peak. Therefore, in this case where there were substantial vertical shifts caused by environmental factors, the change in RMSD values gives a false impression of damage.

Figure 3.4: Conductance signatures against frequency plot for specimen B2 (10 – 100 kHz).

- (a) Patch C (unprotected)
- (b) Patch 3 (protected with silicone rubber A)
- (c) Patch 4 (protected with silicone rubber B)

3.3.3.3 Specimen B3 (indoor condition)

The signatures acquired from the patches placed under room condition (specimen B3) showed even higher consistency (average RMSD value = 2.72%) than those under outdoor condition (specimen B1, average RMSD = 3.56 %). No sign of degradation could be seen after one and a half year of monitoring. The plots are attached in Appendix A.

3.3.3.4 Specimen R

Signatures acquired from patch bonded on cylindrical rock sample fluctuated substantially in the vertical direction throughout the monitoring period as depicted in Figure 3.5. The average RMSD for patches protected by silicone rubber A and by silicone rubber B are virtually the same, 9.72% and 9.81% respectively.

From Figure 3.5, it is obvious that variations of signatures are mainly in the vertical direction. No horizontal movement occurred and the overall shape remained the same. The shift also showed no tendency of moving in any particular direction, but fluctuated within certain range. Thus, it can be inferred that the vertical movement is unlikely to be caused by degradation of the patch, bonding or structure against time. The differences are also unlikely to be caused by instrumentation or measurement problems as the signature acquisition was done within a short period (a few hours) together with other specimens, which performed satisfactorily. One of the possible reasons is the constant fluctuation of internal humidity inside the rock structure which altered the internal damping effect. This observation agrees with the structural dynamic theory where damping affects the vertical movements of the frequency spectrum.

This phenomenon is however, insignificant in other material, such as aluminum, as discussed in previous cases. This is attributed to the fact that the rocks are porous in nature. Water can easily permeate through the pores and trap in between. In tropical country such as Singapore, which is consistently subjected to heavy rain and strong sunlight, substantial fluctuation in humidity is very common. Negligible shift of resonance peak in the horizontal direction implied that the structural stiffness remained unchanged, thus indicating the structure is free from damages.

Figure 3.5: Conductance against frequency plot for specimen R (10 – 100 kHz).

- (a) Patch 7 (protected with silicone rubber A)
- (b) Patch 8 (protected with silicone rubber B)

3.3.3.5 Specimens C1 and C2

Figure 3.6(a) illustrates the conductance against frequency plot for specimen C1, a concrete block with PZT embedded, and placed under room condition. Progressive rightward shift in resonance peaks occurred throughout the period of monitoring. This phenomenon was caused by the stiffening of concrete throughout the process of curing. Substantial curing was expected as the baseline signature was first recorded shortly after the block was cast. Specimen C2 possesses a similar plot.

Fortunately, concrete curing is a gradual progress, hence, if the baseline signatures are continuously updated, damage detection may still be feasible because damage usually causes leftward shift, as oppose to the rightward shift caused by curing. However, more experimental studies are necessary to understand the effect of curing under different circumstances if long term SHM on concrete cube before it is fully cured were to be performed.

A close up into frequency range from 35 to 50 kHz (Figure 3.6b) shows an interesting phenomenon. It verified the ability of the EMI technique in monitoring the curing rate of concrete (Bhalla, 2004). Specimen C1 (patch 9), which was placed in room cured more uniformly due to relatively consistent ambient humidity. For the case of specimen C2 (patch 10) as shown in Figure 3.6(c), which was placed under outdoor condition, curing was more intensive in the first month due to higher humidity (RMSD values after first month of 73.12% for C2 against 30.11% for C1). Subsequent curing of C2, however appeared to be lesser than C1. The curing process continued even up to the time when this thesis is written (more than one and a half year) as reflected from the continuous rightward shifts.

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Figure 3.6: Conductance against frequency plot for specimens C1 and C2.

- (a) Patch 9 (10 – 100 kHz)
- (b) Patch 9 (35 – 50 kHz)
- (c) Patch 10 (10 – 100 kHz)

All the unprotected patches from various samples performed excellently throughout the period of monitoring despite slightly higher fluctuations. The unprotected patch buried in dry soil remained workable without significant degradation. This shows the robustness of the EMI technique against the outdoor environment. With further protection using silicone layer, it provides adequate confidence to the use of the PZT patches in normal construction site which is full of dust and in contact with soil. Under such environment, which can be considered as nominal, both silicone rubber A and silicone B performed equally well.

However, more studies ought to be carried out in exploring more robust protection (one novel method of protection is discussed in the later section), under harsher conditions, as well as longer period of monitoring. Furthermore, the problems caused by humidity in rock and curing of concrete ought to be overcome or compensated.

3.4 Effect of Silicone Rubber

Silicone rubber is known as an excellent protective material especially in water proofing, inert to chemical and able to insulate electricity. It could be conveniently cured at room temperature. In this case, the silicone rubber not only protects the PZT patch from dust and humidity but also prevents the wires soldered to the patch from being jerked off. Commercially available at relatively low price, the silicone rubber is a low cost and easy to apply protection.

Despite the advantages of using silicone rubber, its potential adverse influences on the actuation and sensing capability of the PZT patch ought to be investigated. Bhalla (2004) proved that the use of silicone rubber as protection would not affect the damage detection sensitivity.

Figure 3.7 illustrates the admittance signatures against frequency plot for a PZT patch before and after the application of silicone layer. Slight suppression on resonance peaks' magnitudes and leftward shift in resonance peaks can be observed from signatures below 50 kHz. Above 70 kHz, this phenomenon becomes more obvious. The outcome suggests that the silicone layer resembles a damper which reduced the magnitudes of resonances. Meanwhile, the addition of silicone layer has slightly reduced the overall stiffness of the system as seen from the reduction in modal frequency (Figure 3.7b).

Figure 3.7: Conductance signatures against frequency plot before and after application of silicone rubber.

- (a) Frequency range: 20 – 50 kHz
- (b) Frequency range: 70 – 100 kHz

The average RMSD values computed through 20 – 50 kHz is 17.90% whereas from 70 – 100 kHz is 34.58%. Therefore, it can be concluded that influence of silicone layer is more significant at higher frequency of actuation. This can be explained by the fact that the effective actuation and sensing range of the PZT patch reduces against frequency, which caused the influence of silicone layer to be more significant at higher frequency.

Fortunately, the silicone rubber did not affect the repeatability of the signatures as demonstrated in the previous section. Therefore, even with the silicone layer applied, taking the admittance signatures as baseline will ensure the EMI technique to perform equally well.

3.5 Installation and Workability of PZT Patch

Being a ceramic, a PZT patch is brittle by nature. As the thickness of the PZT patch used in the EMI technique is normally smaller than 1 mm, slight bending during installation can easily break the material. In the lab condition, installation of bare PZT patch onto structure is possible with extra care and with certain handling experience.

However, in actual construction site, direct installation of bare PZT patches onto structures can be very difficult. High rate of failure will render the technique uneconomical. Some of the difficulties have been overcome by Mide (2006) by using installation gadget customized for PZT patch installation.

Throughout the process of experimentation, the author has also found an economical and convenient way for onsite installation. A novel approach was attempted by attaching a PZT patch soldered with wires using silicone rubber, onto an aluminum plate. The thin aluminum plate is slightly wider than the patch, as depicted in Figure 3.8. The bottom face of the patch is left clear from silicone for subsequent bonding onto the host structure.

Figure 3.8: Pictorial representation of a PZT patch protected with thin aluminum plate with soft silicone rubber as interface.

The advantage of this protection method lies in the fact that with the PZT patch protected by the much stiffer aluminum plate, the possibility of bending failure during installation could be eliminated. Tests conducted showed that the aluminum plate, on the other hand, will have very mild effect on the actuation and sensing of the patch with the use of very soft silicone rubber as interfacial adhesive. Initial attempt adopting epoxy as the interface rendered the actuation on protective aluminum plate dominating the host structure, which is highly undesirable.

The aluminum plate could be retained as a long term protection or it could also be removed after the patch is securely bonded to the host structure. The removal could be done easily if some oil is purposely left between the interface of the PZT patch and the structure at the preparation stage.

Once the patch is securely bonded onto the host structure, it will be strengthened considerably by the much stiffer structure and hardened adhesive. Moderate impact force will not cause any damages to the PZT patch even without any protection. Once it is installed, the fragility of the patch is no longer a major concern.

3.6 Concluding Remarks

This chapter presents the long term consistency of the electrical admittance obtained from PZT patches for the application of the EMI technique. Different protections were applied in an attempt to search for an optimum protection, especially under harsh environment.

Repeatability of signatures was excellent especially for patches attached to aluminum beam. The signatures remained highly repeatable even after more than one and a half year. However, the signatures were less stable for those patches attached on rock and concrete due to the problem of constant change in humidity and stiffness (caused by curing) respectively.

Silicone rubber was found to be a useful protection for the PZT patch. The repeatability of signatures appeared to be unaffected by the silicone layer.

Subsequent chapter presents a study on the effect of ambient temperature and bonding layer on the admittance signatures.

CHAPTER 4 EFFECTS OF TEMPERATURE, BONDING LAYER AND OTHER PRACTICAL ISSUES

4.1 Introduction

Due to the nature of piezoelectric material, the EMI technique is sensitive to changes in temperature and humidity. The preceding chapter demonstrated the long term applicability of the EMI technique in SHM under various environments. However, the effects of ambient temperature and humidity were excluded from the study by allowing the specimens to stabilize in the room before the signatures were acquired. This assumption may not be true in real-life applications as the patches would be permanently bonded on the structure. The fluctuations of ambient temperature and internal or external humidity are unavoidable.

Research conducted up to date focused mainly on the effect of temperature on both the PZT patch and the structure (Sun et al., 1995; Park et al., 1999; Bhalla, 2001). Study related to the effect of temperature on bonding layer is rarely found. Nguyen et al. (2004) found that the temperature effect was more pronounce on the viscoelasticity of the bonding film rather than the structure. However, his study concentrated on low frequency range of excitation (few *kHz*) rather than those used in the EMI technique (tens to hundreds of *kHz*).

If a PZT patch were to be surface bonded onto a structure, the adhesive forms the only interface for strain transfer. It is well known that the bonding film is much softer (in terms of stiffness) than the patch and the structure. The stiffness can be further reduced at elevated temperature. Therefore, it is expected that there will be deterioration in performance of the bonding film, which deserves further study.

This chapter describes the experimental investigation of the effect of temperature variation on the admittance signatures acquired, with special attention paid on the influence of bonding layer. Since the application of EMI technique in civil engineering involves only the normal range of temperature, extreme temperature such as cryogenic temperature (Tseng et al, 2003) and temperature above Curie temperature were not considered in this study.

4.2 Review on Studies Related to Effects of Humidity, Temperature and Bonding

4.2.1 Humidity

In tropical country such as Singapore, heavy downpour is a normal phenomenon which maintains its air at relatively high humidity. The National Environment Agency of Singapore (2006) reported a mean value of 84% in relative humidity. Relative humidity can often hit 100% during prolonged heavy rain. Thus, the effect of humidity on the application of the EMI technique is inevitable under such circumstance.

To the best knowledge of the author, very few literatures related to the effect of humidity are available. Bhalla (2004) studied the resistance of the EMI technique to humidity by soaking an aluminum specimen with surface bonded PZT patches into water for 24 hours. It was found that the signatures acquired from the unprotected patch deviated from the baseline despite it had been dried up. The patch protected with silicone rubber was found to perform well upon drying. However, this situation holds only when the host structure itself is not significantly affected by humidity, as described in the previous chapter. More studies related to the long term performance of the silicone rubber and the search for more robust protection are necessary.

4.2.2 Temperature

Temperature changes could lead to changes in mechanical and electrical properties of all components, including the PZT patch, the bonding layer and the host structure. Figure 4.1 portrays the changes of piezoelectric charge constant against temperature for some typical PZT patches (PI Ceramics, 2006). It is therefore essential to investigate their effect on the admittance signatures in the application of the EMI technique. Appropriate compensation technique should also be actively searched.

Figure 4.1: Temperature dependence of piezoelectric charge constant, d_{31} (PI Ceramics, 2006).

Sun et al. (1995) discovered that the variations in electrical impedance caused by thermal drift and damage differ significantly. They showed that temperature causes simultaneous shift of all structural mode whereas structural damage results in abrupt and local impedance variation. Within certain temperature range, temperature induced signatures translation could be viewed as a superposition of vertical and horizontal shift. A function correlation analysis was proposed to mathematically compensate the horizontal signatures shift. If $X(r)$ and $Y(r)$ are the signatures at two different temperatures, then the horizontal shift of τ data points between them shall be such that the following correlation coefficient is equal to unity:

$$\rho_{XY}(\tau) = \frac{R_{XY}(\tau)}{\sqrt{R_X(0)R_Y(0)}} \quad (4.1)$$

$$R_{XY}(\tau) = \frac{1}{N} \sum_{r=1}^{r=N} X(r)Y(r+\tau) \quad (4.2)$$

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where $R_X(0)$ and $R_Y(0)$ are auto correlation functions of X and Y . N represents the total number of data points adopted for the calculation. Through trial and error, the signature Y is shifted by τ data points until the two signatures matched each other.

Krishnamurthy et al. (1996) investigated the temperature effect on free PZT patch. Schultz et al. (2003) reported that the piezoelectric properties decreased with increasing temperature but recovered each time the sensor almost cooled, as long as the Curie temperature was not exceeded. They also studied the performance of the PZT patch as well as the bonding film at high temperature ($> 100\text{ }^{\circ}\text{C}$).

Park et al. (1999) conducted some experimental studies on bolted pipe, composite reinforced aluminums and precision parts such as gears. They illustrated that temperature change affected the dielectric constant and piezoelectric coupling constant of the patch. Slight effect was also found towards the Young's modulus of the structure. They also discovered that the reactive (real) portion of signatures acquired from free-ended PZT patch changed insignificantly with temperature. Therefore, the reactive portion was preferred over the imaginary component when used in the EMI technique. They commented that the cross correlation method proposed by Sun et al. (1995) would not work if the signature has small distortion and can only make correction for horizontal shift.

For real-life application, a compensation technique based on analytical model incorporating the effect of temperature may not be practical due to the complex constitutive thermo-electrical-mechanical model of piezoelectric materials involved and also the requirement of the complicated modeling of the host structure (Kabeya, 1998). An empirical based temperature compensation technique was proposed by Park et al. (1999). This technique is based on the assumption that both the vertical and horizontal shifts of signatures caused by temperature changes are uniform across a narrow frequency range. Therefore, the distorted signatures can be conveniently shifted back to the original position through separately shifting them horizontally and vertically.

In this technique, the signatures are first compensated vertically by searching the average vertical difference between the two targeted signatures (Park et al., 1999):

$$\delta_v = \frac{\sum_{i=1}^n \text{Re}(Z_{i,2})}{n} - \frac{\sum_{i=1}^n \text{Re}(Z_{i,1})}{n} \quad (4.3)$$

where δ_v is the average vertical shift, $Z_{i,1}$ is the original (baseline) admittance signatures at frequency interval i , $Z_{i,2}$ is the signatures at frequency interval, i with different temperature and n is the total number of data points selected for compensation.

With the vertical difference obtained, subsequent compensation on the horizontal shift is achieved by minimizing the damage metric between the two signatures within the frequency range of interest:

$$M = \sum_{i=1}^N [\text{Re}(Z_{i,1}) - \{\text{Re}(Z_{i+\delta_h,2}) - \delta_v\}]^2 \quad (4.4)$$

where M is the damage metric and δ_h is the horizontal shift (shift in discrete frequency). The empirical nature of this technique enables itself to be conveniently applied on all kinds of structures.

Nguyen et al. (2004) investigated the change in actuation efficiency of the PZT patch due to varying temperature and different adhesive layers. They found that temperature effect was more pronounced on the viscoelasticity of the bonding layer rather than the structure.

Bhalla (2001) studied the effect of temperature through numerical simulation to isolate each piezoelectric property for independent study. He drew similar conclusion as Park et al. (1999) where the parameters susceptible to temperature variations were the structure's Young's modulus (caused horizontal shift), as well as the PZT patch's dielectric constant and coupling constant (both caused vertical shifts). The effect of material's Poisson's ratio and volume expansion were found to be negligible.

Kabeya (1998) performed an analytical study to investigate the variation in structural response caused by temperature on a simple steel beam with free-free boundary condition. The analytical model was found to be well correlated to the experimental outcome. However, the model was limited to simple beam structure and only the shifts in resonance frequencies were investigated.

4.2.3 Bonding layer

In the application of EMI technique, studies related to the effect of temperature up to date have focused mainly on its effect on the structure and the PZT patch as reflected from the available literatures. The effect on admittance signatures caused by the bonding layer under varying temperature on the PZT – structure interaction, has often been omitted.

Crawley and de Luis (1987) proposed a static based model and Ha et al. (1992) proposed a dynamic FE model on the PZT – structure interaction. Both methods ignored the excitation frequency. This is highly impractical for the EMI technique, which utilizes high frequency of excitation.

Nguyen et al. (2004) studied the actuation efficiency of PZT patch under varying ambient temperature and adhesive thickness. It was found that the effect of temperature was more pronounced on the bonding layer rather than the structure. They also concluded that increase in bonding thickness would cause more losses in terms of actuation power than an increase in temperature. They also unveiled that the hardness reduction of adhesive due to higher temperature or increase in thickness of bonding would reduce the local stiffening effect of the actuators on the host structure and the overall stiffness of the system. However, the adverse effect such as shift in eigen frequency was found to be relatively small. Again, their study was based on low frequency of actuation ($< 4\text{ kHz}$) which may not be representative for the case of the EMI technique.

Xu and Liu (2002) incorporated the effect of bonding into the 1-D impedance based electromechanical model (Liang, 1994) by simplifying the bonding film into a single spring-mass-damper system placed in between the PZT patch and the structure.

Ong (2003) studied the effect of bonding through analytical and numerical models. In the analytical model, he attempted to incorporate the effect of bonding by varying the effective dimension of the PZT patch based on the shear lag model. He also showed that a stiffer adhesive would produce stronger resonance in the admittance spectrum but has no effect on the modal frequency.

Bhalla (2004) proposed a 2-D effective impedance based model inclusive of the adhesive layer. It was found that when the shear lag effect was larger than 30, the effective length

would be more than 93% of the initial length. Under such context, he concluded that the effect of bonding could be omitted for most engineering models. He also conducted parametric study using the model to investigate the effect of patch's length, bonding thickness, shear modulus of the bonding, etc. on the admittance signatures.

The following sections elucidate various experimental based investigations into the effect of bonding and temperature.

4.3 Experimental Study

4.3.1 Specimens preparation and experimental setup

Figure 4.2 illustrates a series of specimens prepared for the test, consisting of an aluminum beam, an aluminum plate, a concrete cube and a rock (fragment of granite), all surface-bonded with one or more PZT patches. The details of each specimen including the size of the structure, and the bonding thicknesses are summarized in Table 4.1. The dimensions of all patches used in this study were $10\text{mm} \times 10\text{mm} \times 0.3\text{mm}$. All structures can be considered as being actuated under free-free boundary conditions as they were all placed on some thick and soft tissue papers during the test without any end constraints.

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Figure 4.2: Lab-sized specimens surface-bonded with PZT patches (10mm x 10mm x 0.3mm).

- (a) Aluminum beam
- (b) Aluminum plate
- (c) Rock (Fragment of granite)
- (d) Concrete cube
- (e) Freely suspended PZT patches

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Table 4.1: Summary of locations of PZT patches, bonding thickness and specimens' details.

Host structures	Size of structures	Patch label	Measured bonding thickness (mm)	Thickness of optical fiber (mm)	Descriptions
Aluminum beam	331mm x 31mm x 6mm	b1	0.04	-	1. Thin bonding 2. Placed at symmetrical locations (inside)
		b2	0.03	--	
		B3	0.14	0.10	1. Thick bonding 2. Placed at symmetrical locations (near both ends)
		B4	0.22	0.14	
Aluminum plate	302mm x 201mm x 4mm	p1	0.05	--	1. Thin bonding 2. Placed at symmetrical locations
		p2	0.06	--	
		P3	0.13	0.10	1. Thick bonding 2. Placed at symmetrical locations
		P4*	0.21	0.14	
Rock fragment	--	r	Not measured	--	
Concrete cube	150mm	c	Not measured	--	
Free PZT patch	10mm x 10mm x 0.3mm	F1	--	--	Hang freely in air without any bonding
		F2	--	--	

* Patch P4 was spoilt in the beginning of the experiment.

The patches bonded on both the aluminum plate and beam were carefully arranged in a symmetrical manner. This enabled the comparison of admittance signatures for different

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bonding thickness but with identical PZT – structure interactions. The adhesive used was the same as those described in the previous chapter.

During the process of installation, surfaces of the host structure and the PZT patch were properly cleaned to remove all dirt in order to obtain the possible thinnest bonding film on flat surface. Static weight was applied on top of the PZT patch during curing (24 hours) to attain maximum bonding strength at minimum possible thickness. Patches labeled b1, b2, p1, p2, r and c were prepared in such manners. They can be identified through small alphabet prefix, indicating thin bonding.

Bhalla (2004) proposed a method of controlling the bonding thickness by inserting a pair of known thickness, optical fiber in between the structure and the PZT patch. With this, the thickness of bonding was assumed to be equal to the thickness of the fiber. The effect of the fiber on the PZT's actuation was assumed to be negligible. This method was adopted for patch labeled B3, B4, P3 and P4, all possessing capital prefix, implying thick bonding. Patches B3 and P3 were bonded with *0.1mm* optical fiber and patches B4 and P4 with *0.14mm* optical fiber.

According to the recommendation by Bhalla (2004), when the thickness of bonding is smaller than one third of the thickness of PZT patch, the effect of bonding is negligible. In this case, one third of the PZT's thickness was *0.1mm*. Therefore, patches b1, b2 and p1, p2 fell under the category of “less than one third” (here denoted as “thin”) whereas patches B3, B4 and P3, P4 were within the category of “more than one third” (hereafter denoted as “thick”).

Two instruments, namely the displacement transducer and micrometer screw gauge, both with sensitivity of *0.001mm* were used to measure the thickness of the bonding film. During the measurement, it was found that considerable fluctuations occurred in the third decimal places for the measured thickness. The results were therefore round off to second decimal places, which was more stable and practical. The measurements taken by both displacement transducer and micrometer screw gauge were found to be sufficiently closed.

The minimum thickness obtained in this setup was $27\mu\text{m}$, slightly larger than the value of $15\mu\text{m}$ reported by Nguyen et al. (2004). On the other hand, the assumption made by Bhalla (2004) stating that the thickness of bonding can be viewed as the same as the thickness of the

optical fibers placed in between was found to be not exact. The actual thickness would be slightly larger than the fiber's thickness, as revealed in Table 4.1. However, the two values were sufficiently close.

In order to study the various effects such as those caused by the bonding thickness, temperature, damage, repeatability, etc. on the admittance signatures against frequency spectrum, the experiments were conducted in stages. In general, for each stage, the admittance signatures of each PZT patch were obtained for a predetermined frequency range. Subsequent acquisitions of signatures after the system has undergone certain changes would be compared against the baseline. This chapter mainly describes the experimental study, with qualitative analyses using the admittance signatures against frequency spectrum. Chapter 5 presents the relevant numerical verification.

4.4 Effect of Bonding

In the application of EMI technique, the sizes of the bonding film and the PZT patch are considerably smaller than the host structure. The bonding layer is also much weaker than the structure and the patch in terms of stiffness. It is therefore reasonable to say that the PZT patch and the bonding film should not significantly affect the vibration mode of the host structure as reported in previous studies.

As illustrated in Figure 4.3, high repeatability of the conductance signatures could be observed for patches bonded on symmetrical locations on the plate specimen but with different bonding thickness. In other words, they possess identical PZT-structure interaction but with different bonding thickness. All resonance peaks could be accurately matched indicating that the PZT patches were consistent in the process of actuating and sensing. This further confirmed the consistency and reliability of the EMI technique. However, slight variations are expected especially in the higher frequency range, as depicted in Figure 4.4. Some of the local peaks are not repeatable. At high frequency range, the sensitivity of admittance signatures to local changes was very high. Slight difference in bonding thickness or placement locations would change the admittance signatures. Similar observations could be found in the patches bonded on beam specimen.

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Figure 4.3: Conductance against frequency plot for PZT patches bonded on plate specimen with different bonding thickness but identical PZT-structure interaction (10-20 kHz).

- (a) Patch p1
- (b) Patch p2
- (c) Patch P3

Figure 4.4: Conductance against frequency plot for PZT patches bonded on plate specimen with different bonding thickness but identical PZT-structure interaction (80-90 kHz).

(a) Patch p2

(b) Patch P3

When the frequency exceeded *100 kHz*, the situation became worse as shown in Figure 4.5. Most of the resonance peaks were not repeatable. Moreover, it is observed that the overall signatures for patch P3 (thicker bond) were shifted upwards. This effect has also been observed by Bhalla (2004) and Ong (2003).

Figure 4.5: Conductance against frequency plot for PZT patches bonded on plate specimen with different bonding thickness but identical PZT-structure interaction (220-240 kHz).

(a) Patch p2

(b) Patch P3

The reason for this effect can readily be explained if the frequency spectrums of patches with different bonding thickness are plotted for a larger bandwidth (0 - 1000 kHz) as illustrated in Figure 4.6. Observing the frequency plot for free-ended PZT patch (no bonding) on Figure 4.6(c), there were a number of strong PZT patch's resonance peaks within the range. When compared with those bonded on the structure (Figure 4.6a and Figure 4.6b), resonance peaks of free PZT patch were much smoother and occurred at significantly lower frequency.

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This is attributed to the fact that when the PZT patch was bonded on the structure, it was significantly stiffened by the structure. Therefore, the peaks of the bonded PZT patches were shifted to the right, indicating an affect of stiffening.

On the other hand, comparing Figure 4.6(a) and Figure 4.6(b), the PZT patch's resonance of P3 occur earlier (more to the left) than p2. This phenomenon could be explained by a decrease in strain transfer efficiency (due to more significant shear lag effect) with thicker bonding, thus "isolating" the PZT patch from the structure. With a decrease in PZT patch's actuation on the structure, the patch tended to actuate independently instead of actuating the whole system. Subsequently, the leftward shift of the first PZT patch's resonance forced the structural resonance peaks in between $100 - 300 \text{ kHz}$ vertically upwards as observed in Figure 4.5(b).

Similar observation could be seen in the case of beam specimen. This explanation is numerically verified in the next chapter. Therefore, the recommendation given by Bhalla (2004) stating that the bonding thickness ought to be less than one third of the PZT patch's thickness was further verified. Thick bonding should be avoided to reduce the contamination on the structural resonance peaks caused by PZT patch's resonance.

On the other hand, it can be concluded that the frequency range used in the EMI technique (for surface bonded patches) is preferably lower than 200 kHz , unless a sufficiently thin bonding could be assured. The requirement would be more stringent at elevated temperature as the abovementioned adverse effect would be significantly amplified, which will be discussed in later sections.

There is another noteworthy phenomenon in Figure 4.6. At very high frequency range, significant localized actuation of the PZT patch caused the peak between $700 - 800 \text{ kHz}$ (Figure 4.6b) to occur virtually at the same location (same resonance frequency) as its counterpart in Figure 4.6(c), indicating that their actuation on structures at this frequency were highly inefficient. The patch was almost vibrating independently. It is expected that this is a general phenomenon, although the plots of different cases may vary with different sizes of patches, different type of bonding and host structures.

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Figure 4.6: Conductance against frequency plot for PZT patches with different bonding thickness (0 - 1000 kHz).

- a) Patch p2 (bonding thickness = 0.06mm)
- b) Patch P3 (bonding thickness = 0.13mm)
- c) Patch F1 (no bonding)

4.5 Effect of Temperature

All the specimens described in the previous section (Figure 4.1 and Table 4.1) were reused for investigation on the effect of temperature. The admittance signatures of the PZT patches were acquired at various predetermined ambient temperatures. Elevated temperature was achieved by placing the specimens in a temperature chamber, which is capable of changing and maintaining its interior temperature. Starting from room temperature, 30°C (baseline), temperature in the chamber was gradually increased to 35°C, 40°C, 45°C, 50°C, 60°C and 80°C.

The temperature chamber enabled the user to manually control the internal temperature. However, to reassure that the required temperature was attained, two thermocouples were placed inside the chamber, next to the specimens for more accurate temperature measurement. The thermocouples also help to determine whether the internal temperature is the stipulated value. A stabilizing time of about 10 minutes was allowed for each cycle for the specimens to attain steady state temperature.

Park et al. (1999) found that the real (resistive) component of the impedance is more reactive to change in damage and the imaginary (reactive) component is more susceptible to temperature effect. It was also discovered that the real component of the signatures from a free PZT patch is insensitive to temperature. Therefore, it would be more sensible to adopt the resistive, rather than the reactive component, so as to minimize the interference from the temperature change.

4.5.1 Adverse effect of bonding at elevated temperature

Figure 4.7: Conductance against frequency plot for PZT patch, b2 bonded on beam specimen with ambient temperature at 30°C and 40°C (30 - 40 kHz).

Figure 4.7 illustrates the typical effect of temperature on the admittance signatures of PZT patches. In this case, the patch was bonded on a beam structure. Effect of rise in temperature could be viewed as an effect of ‘softening’ which reduces the overall stiffness as revealed from the uniform reduction in resonance frequency for all the peaks. This effect would be more pronounced with increase in temperature or at higher frequency range.

Beside the abovementioned factors, another crucial factor often overlooked is the adverse influence of bonding layer at elevated temperature. At high temperature, the admittance signatures acquired from patches of thicker bonding layer exhibits more severe deviation as illustrated in Figure 4.8. With similar PZT-structure interaction, signatures acquired from patch B4 (0.22mm) (Figure 4.8b) underwent significant upward shift when compared to the one from patch B3 (0.14mm) (Figure 4.8a).

This phenomenon was caused by the leftward shift of the first PZT resonance peak due to similar reason described in the previous section. In this case, the increase in temperature significantly reduced the stiffness of bonding and thus amplified the shear lag

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effect. The PZT patch was again isolated from the structure and dominated over the structural vibration.

The leftward shift in first PZT resonance peak (Figure 4.8c) forced up the signatures representing the structural vibration near its left end. With thick bonding ($>1/3$ of PZT patch thickness), the effect was significant and undesirable. With $10\text{ }^{\circ}\text{C}$ difference in temperature and with frequency less than 100 kHz , the shift in signatures could be efficiently compensated even for case B4 (will be illustrated in later section). However, this effect can be intolerable at larger temperature difference and at higher frequency range.

Figure 4.8: Conductance against frequency plot bonded on beam specimen with ambient temperature at 30°C and 40°C.

- (a) Patch B3 (90 - 100 kHz)
- (b) Patch B4 (90 - 100 kHz)
- (c) Patch B4 (0 - 1000 kHz)

Plotting on the same scale (Figure 4.9), we can see the momentous adverse effect of temperature on admittance signatures, especially when the bonding layer was thick (Figure 4.9b). The deviation was however, insignificant in the case of thin bonding (Figure 4.9a). A temperature difference as large as 50 °C (between 30 °C and 80 °C) caused only minor distortion even up to 150 kHz. In comparison to Figure 4.9(b), significant deviation has occurred even with a difference of merely 10 °C.

A close up into frequency range of 80 – 100 kHz between 30 °C and 60 °C (Figure 4.10) for both cases further indicated the adverse effect of thick bonding at high temperature. Beside upward shift in signature, the actuation of patch B4 became very weak as seen from the diminished peaks' amplitudes. The shapes of resonance peaks were also distorted.

It can therefore be concluded that with the use of normal adhesive, such as two parts epoxy in this case, thick bonding is highly undesirable. Also, the frequency range used for the EMI technique is preferably lower than 100 kHz for a more reliable and efficient application. The problem may be alleviated with the use of temperature insensitive adhesive but the

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adverse effect is expected to be the same.

It should be noted that the softening of bonding film due to elevated temperature will only affect the signatures vertically. However, it does not affect the modal frequencies of the host structure.

Figure 4.9: Conductance against frequency plot for PZT patches bonded on beam specimen with ambient temperature varying from 30°C to 80°C (0 - 300 kHz).
(a) Patch b2
(b) Patch B4

Figure 4.10: Conductance against frequency plot for PZT patches bonded on beam specimen with ambient temperature varying from 30°C to 60°C (80 - 100 kHz).

(a) Patch b2

(b) Patch B4

4.5.2 Sensitivity to temperature

In real-life SHM, fluctuation in temperature is inevitable. Under tropical climate, the fluctuation is however, expected to be relatively small. The National Environment Agency of Singapore (2006) reported that the diurnal range of temperature in Singapore falls between 23°C and 34°C.

It is useful to know the sensitivity or tolerance of the EMI technique to temperature. In other words, this is to know what temperature difference should demand the compensation technique be applied.

With 5°C difference in temperature, significant horizontal shift occurred for frequency range higher than 80 kHz, as shown in Figure 4.11(b). However, the effect was insignificant when the frequency was lower than 40 kHz as depicted in Figure 4.11a. Therefore, temperature compensation would be necessary even with narrow temperature fluctuation.

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Figure 4.11: Conductance against frequency plot for PZT patches bonded on beam specimen with ambient temperature varying from 30°C to 35°C.

(a) Patch b2 (30 - 40 kHz)

(b) Patch b2 (80 - 90 kHz)

4.5.3 Application of temperature compensation technique

As described in the previous sections, shifting of the admittance signatures due to temperature changes is inevitable. A reliable, effective, real-time, autonomous and easy to apply temperature compensation technique is therefore necessary to compensate the undesirable effect. In this study, the empirical based compensation technique proposed by Park et al. (1999) was adopted.

4.5.3.1 Software based temperature compensation algorithm

For the ease of application, the computational procedures for temperature compensation based on Equation (4.3) and Equation (4.4) were written into program code using Matlab version 6.5 (Palm, 2001). The software is customized in such a way that it would first automatically calculate the average vertical difference throughout the user defined frequency range between two sets of selected admittance signatures. It would then automatically compensate the vertical difference in between. Finally, it would search for an optimum horizontal shift (in terms of kHz) by trial and error to compensate for the horizontal difference. The list of *Matlab* commands is attached in Appendix B.

The program was written in such a way that it possessed user friendly interface. The users could select the range of frequency for compensation as well as specify the number of times for trial and error. For each PZT patch, the program will automatically produce output files (in both data and graphic forms) containing the signatures acquired at baseline temperature, altered temperature as well as the compensated signatures. The program will also automatically search for the optimum horizontal shift for appropriate compensation. It should be noted that the signatures of relatively lower temperature were always taken as the baseline for compensation in this study.

A sample of the user interface and corresponding output in *Matlab* environment is illustrated in Figure 4.12, whereas an example of successful application (in graphical form) of the technique is plotted in Figure 4.13. All the peaks were accurately shifted back to their original positions after compensation despite some minor changes in their amplitudes.

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User Input: Start frequency (kHz) = <u>80</u> End frequency (kHz) = <u>100</u> Number of trials for horizontal shift search (each shift = 0.1 kHz) = <u>10</u>
Matlab Output: The average vertical shift, delta v = <u>2.167e-5 G</u> The optimum horizontal shift, delta h = <u>0.8 kHz</u> Damage index: Before compensation = <u>1.073e-5</u> After compensation = <u>5.307e-6</u>

Figure 4.12: User friendly interface and corresponding compensated output in Matlab 6.5 environment.

Figure 4.13: Conductance against frequency plot for PZT patch, b2 bonded on aluminum beam specimen at varying temperature.
(a) Between 30°C and 60°C (90 – 98 kHz)
(b) Between 30°C and 40°C (160 – 168 kHz)

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When the bonding was relatively thin, the effect of vertical shift was visually undetectable, such as for patch b2, even with a $30\text{ }^{\circ}\text{C}$ difference (Figure 4.13a). At higher frequency range, such as those larger than 150 kHz (Figure 4.13b), the compensation technique worked well, too.

On the other hand, for thicker patch such as patch B4, application of the compensation technique was also feasible as shown in Figure 4.14, though not as efficient as for the previous case. This is mainly due to excessive vertical shift caused by the PZT peak's leftward shifting effect as described previously, especially at large temperature variation (Figure 4.14b). It is obvious that the compensated signatures could not return to its original position effectively. This was accompanied by undesirable reduction in peaks' magnitudes due to weaker actuation at higher temperature. This effect was trivial in the case of thin bonding layer as shown earlier.

Figure 4.14: Conductance against frequency plot for PZT patch, B4 bonded on aluminum beam specimen at varying temperature.

(a) Between 30°C and 40°C (90 – 98 kHz)

(b) Between 30°C and 60°C (80 – 88 kHz)

It was found that the empirical equations (Equation 4.3 and Equation 4.4) could not be applied directly under certain circumstances. For instance, the assumption that all signatures shift horizontally and vertically in a uniform manner is not necessary true for all resonance peaks as some of the peaks might be diminished or amplified after the change in temperature.

This could be due to the frequency step (0.1 kHz in this case) adopted is not sufficiently small to reflect the true height of the peaks. On the other hand, it could be caused by the reduction in the strain transfer capability of the adhesive at elevated temperature. Under such circumstance, simply searching for vertical difference, δ_v , through obtaining the average difference is not appropriate. This is because some of the peaks' values differed so much that it significantly exceeded the average difference, rendering the evaluated average value dominated by the peaks' difference instead of the average difference. Similar limitation existed in the search of horizontal compensation, δ_h . The program was thus slightly modified by neglecting the values of peaks while calculating the vertical average so as to overcome this shortcoming (Appendix B).

A summary of vertical shift, horizontal shift, and damage index obtained using the software based empirical temperature compensation technique is tabulated in Table 4.2.

4.5.3.2 Application to non-metal and general structures

Potential application of this empirical temperature compensation technique was attempted on non-metal and general structures as depicted in Figure 4.15. Its robustness was further verified through the successful applications in both concrete cube and granite rock. Empirical nature of the technique renders itself widely applicable by saving the hassle of complex modeling, which is impossible for complex, real life structures.

Figure 4.15: Conductance against frequency plot for PZT patch bonded on non-metal at varying temperature.
(a) Patch c (concrete) between 30°C and 50°C (38 – 48 kHz)
(b) Patch r (rock) between 30°C and 60°C (18 – 28 kHz)

An interesting phenomenon could be observed in the case of rock fragment in Figure 4.15(b) where a significant temperature difference of 30°C caused practically no horizontal shift in the resonance peaks. This might be due to the nature of rock structure which possesses lower expansivity and thus lower reduction in stiffness upon increase in temperature when compared to metal such as aluminum. This observation also indirectly verified that the horizontal shift in frequency spectrum is mainly caused by a change in host structural stiffness. As revealed in this case, despite both the bonding layer and the PZT patch were concurrently being heated with the structure, the peaks remained the same horizontally indicating that both of them have no effect on the horizontal shift.

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Table 4.2: Summary of vertical shift, δ_v , horizontal shift, δ_h and damage index, DI obtained using software based empirical temperature compensation technique.

Patch label	Description*	Temperature range (°C)	Frequency range (kHz)	δ_v (G)	δ_h (kHz)	DI	
						Before compensation	After compensation
b2	Thin	30-40	10-30	7.4e-7	<0.1	6.3e-9	3.6e-9
			80-100	4.1e-6	0.2	1.1e-5	5.1e-6
			150-170	1.7e-5	0.5	2.0e-5	3.8e-6
		30-60	10-30	4.8e-6	0.2	1.5e-8	8.7e-9
			80-100	2.2e-5	0.8	1.1e-5	5.3e-6
B4	Thick	30-40	10-30	7.7e-6	0.1	6.9e-9	2.1e-9
			80-100	3.7e-5	0.2	3.9e-6	2.2e-6
			150-170	1.6e-4	0.5	2.2e-5	4.1e-6
		30-60	10-30	2.6e-5	0.2	1.6e-8	1.3e-8
			80-100	1.9e-4	0.7	2.8e-6	2.0e-6
C	Thin	30-50	30-50	2.1e-6	0.5	2.8e-10	2.7e-11
		30-60	30-50	6.7e-6	1	4.6e-10	1.2e-10
R	Thin	30-40	10-30	4.1e-7	0	2.0e-11	2.0e-11
		30-50	10-30	1.3e-6	0	4.5e-11	4.5e-11
		30-60	80-100	1.1e-5	0.4	7.4e-9	7.3e-9

* Thin and thick indicate the bonding thickness is thinner and thicker than one third of the patch thickness respectively.

4.5.4 Damage detection under varying temperature

Due to the nature of the EMI technique which utilizes admittance signatures for damage detection, any contamination in the signatures could lead to ambiguity during the process of analysis, thus giving false alarm. Park et al. (1999) has confirmed the damage detection

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capability of the EMI technique under temperature difference up to 37.5°C .

In order to investigate the effectiveness of the EMI technique in damage detection under varying temperature, damages in the form of drilled holes and notches were induced on the aluminum beam specimen. Signatures were then reacquired at different temperature.

Figure 4.16 clearly indicates that the temperature compensation technique efficiently compensated the deviation caused by temperature changes and retained the damage detection capability of the EMI technique. In this case, damage was induced in the form of drilled hole.

Without performing the compensation (Figure 4.16a), identification of damages was difficult as the leftward shifts of peaks due to both damage and temperature could hardly be differentiated. After the compensation (Figure 4.16b), damage induced shift can be clearly distinguished from temperature induced shift. Once again, it could be seen that the peaks' magnitude varied at different temperature upon compensation. It is therefore inappropriate to identify damage through change in peaks' height.

Figure 4.16(c) further reveals the effectiveness of this technique as it remained robust for damage detection at elevated temperature (40°C) instead of at baseline temperature (30°C). The same compensation factors were adopted to convert the baseline (30°C) signatures to signatures at elevated temperature (40°C) for damage detection at elevated temperature. The robustness would hardly be achieved if methods involving modeling are adopted.

Figure 4.16: Conductance against frequency plot for PZT patch, b2 bonded on aluminum beam specimen at varying temperature with damage induced (93 – 98 kHz).

- (a) Without compensation for undamaged state at 30°C
 (b) With compensation for damaged state at 30°C
 (c) With compensation for damaged state at 40°C

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Similar observations could be made for the case of aluminum plate (not shown) and for other frequency ranges. Compensation for PZT patch with thick bonding should also be possible though it may suffer from higher contamination. Again, high frequency range (> 100 kHz) is not recommended because closely spaced peaks at higher frequency range renders identification of their movements very difficult.

Another way of differentiating between temperature induced and damage induced signatures' deviation is by observing the admittance signatures at very high frequency range ($200 - 1000$ kHz) as exemplified in Figure 4.17. Temperature induced deviation triggered the shift of PZT patch's resonance peaks at higher frequency range (Figure 4.17a) which did not exist in the case of damage. Figure 4.17(b) illustrates that the high frequency range was virtually unaffected by damages on the host structure (as long as the PZT patch remains intact). In this case, the frequency spectrum at higher end remained unaffected in spite of serious damage inflicted, in the form of drilled holes and cut notch.

This approach undeniably provides a fast guide to the inspector for differentiating damage from temperature, with merely a glance at the admittance signatures plot for high frequency range. However, this approach is more effective for the case of thick bonding, which is undesirable. More discussions related to damage on the PZT patch is presented in the ensuing section.

Figure 4.17: Conductance against frequency plot for PZT patch, B4 bonded on aluminum beam specimen for frequency range 0 – 1000 kHz.
(a) Temperature varies from 30°C to 60°C
(b) Damages induced at 30°C

4.5.5 Shortcomings and countermeasures of temperature compensation technique

Despite the robustness of the empirical temperature compensation technique described previously, shortcomings exist and appropriate countermeasures are necessary to ensure its reliability in real life application.

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One of the apparent shortcomings is that the uniformity of horizontal and vertical shifts caused by temperature changes is only valid within narrow frequency range. Throughout the numerous tests conducted by the author, it was found that the range of frequency selected for each application of compensation should not exceed 20 kHz . The frequency range should be further reduced to 10 kHz at larger temperature difference or for patches with thicker bonding. This inadvertently requires a large number of compensation factors (δ_v and δ_h) for each PZT patch. For instance, if the frequency range adopted for monitoring is set to be $0 - 150\text{ kHz}$, it would require 15 pairs of compensation factors for one particular temperature. Further requirement where different temperature requires different compensation factors would render the technique tedious.

If the numbers of patches used are large, say in the case of civil structural monitoring, handling of the amounts of data can be laborious. Nevertheless, this problem could be considerably alleviated when the data processing and storage are performed by fully automated software.

Another problem is the necessity to first obtain the signatures at both baseline and all elevated temperature before the evaluation of compensation factors is possible. This may not be feasible in real life SHM when immediate monitoring is compulsory after installation of the patch.

However, this could be overcome by constructing a temperature compensation chart, listing all recommended compensation factors for different materials under different temperature and frequency range. This is feasible because the shift in signatures caused by temperature is usually small and could be uniform for each type of materials. In contrary, damage induced changes are usually more drastic and significant than those caused by temperature. Setting up of such chart requires plenty of experimental tests and preferably supported with appropriate analytical and numerical studies.

On the other hand, this shortcoming may not be as serious in tropical region where the fluctuation in temperature is relatively small throughout the year. Pseudo real time monitoring using the EMI technique can be achieved by acquiring signatures at specific time for each day. For instance, baseline admittance signatures could be acquired when the PZT patch is first installed say four times in a day, at 3am, 9am, 3pm and 9pm, with temperature at each interval

recorded. These four periods would probably include the minimum and maximum temperature of a day. Taking the four values as baseline, subsequent monitoring could be performed at the same timing in a day by automated software. Signatures acquired could be compared to their respective counterparts. This method assumes that the temperature remains sufficiently close to each other at the same time of a day. Special case such as during rainy day could be treated separately. Using the same idea, this method could be extended for the compensation of the effect of humidity, as well.

4.6 Damage Detection, Quantification and Identification

4.6.1 Damage detection capability of EMI technique

Ability of the EMI technique in damage detection has been widely accepted in the field of engineering since the last decade. Unique characteristic of the piezo-impedance transducer, which could act as collocated actuator and sensor enables it to reflect the vibrational modes of the structure through the measured admittance signatures. The EMI technique enables powerful qualitative based damage detection through comparing the admittance against frequency plot. The nature of the EMI technique avoids the hassle of model building and complex analysis, which renders the technique easy and economical to apply.

However, inherent limitations inevitably exist. A typical example is the lack of well established method for damage or failure mode identification. Being qualitative in nature, it is very difficult to identify the type of damage that is occurring in the structure merely through analyzing the admittance signatures.

Various researchers have proposed a wide range of non-parametric based damage quantifiers, as described in the previous section. Similar to other non-parametric based approaches, they suffer from shortcomings such as loss of insight into the physical changes occurring in the structure.

Unlike other smart materials such as optical fiber, the EMI technique could only indirectly reflect the changes in structural vibration. This problem is amplified when the ambient effects join in, to contaminate the admittance signatures.

Despite the limitations stated above, the EMI technique would be useful if it is wisely utilized. A number of feasible approaches are summarized below.

4.6.2 Establishment of standard damage calibration and environmental effect compensation chart

Identification of changes or damages in the host structure, to some extent can be qualitatively identified. For instance, compression on host structure causes uniform leftward shift of all admittance signatures but tension causes uniform rightward shift (Abe et al., 2002; Ong, 2003), local damages (Lim et al., 2006) such as cracking results in random and non-uniform shift in resonance peaks, severe damage will lead to a total change in the pattern of signatures, etc.

Therefore, appropriate damage calibration chart could be established through numerous experimental studies accompanied by analytical and numerical models for different types of damages on different structures. With the aid of the chart, the inspector could easily identify the type of damage through observing the admittance against frequency plot. This however, requires tremendous efforts before reliable chart could be established.

4.6.3 Integrated use with other smart materials to form smart structures

Different smart materials possess inherent capabilities which are useful in SHM but at the same time also disturbed by innate shortcomings. An innovative way would be to integrate various kinds of smart materials to complement each other in forming a more robust smart system.

For instance, optical fiber possesses exceptional advantage in strain measurement and the EMI technique is robust in detecting local structural changes without strain. Incorporating the two could lead to a comprehensive monitoring system. With the use of shape memory alloy (SMA), auto repair of the damaged structure could be achieved (Peairs et al., 2004).

Integrated use of the EMI technique and fiber Bragg grating (FBG) has been attempted in this study and is presented in Chapter 6.

4.6.4 Differentiating between damage on host structure and on PZT patch

The previous section illustrated the technique of differentiating the effect of damage on host structure from the effect of temperature on admittance signatures. In this section, study was conducted to differentiate the damage on the PZT patch from the effect of temperature and damage on host structure.

Figure 4.18 depicts the admittance signatures against frequency plot for PZT patch inflicted with different levels of damage by cutting the patch using a pen knife without damaging the wires. Level S1 indicated a cut through the PZT patch from its center whereas level S2 was more severe cut through the center of the PZT patch from another direction. Visually, the PZT patch appeared to be severely spoiled after damage level, S2 as some fragments of the patch had fell off.

However, it was surprising to find that the admittance signatures remained practically the same within the useful range of frequency ($< 150\text{ kHz}$) for damage detection despite second level of damage (S2) been induced on the PZT patch (Figure 4.18a). The damage on the patch could be reflected from Figure 4.18(b) through the higher frequency range ($> 200\text{ kHz}$). Significant shift in the PZT's resonance peaks indicated the damage induced on the patch.

Figure 4.18: Conductance against frequency plot for PZT patch, b1 bonded on aluminum beam specimen with different level of damages (S1 and S2) induced on PZT patch.
(a) Frequency range between 70 – 80 kHz
(b) Frequency range between 0 – 1000 kHz

This interesting phenomenon was attributed to the fact that the structural peaks excited at lower frequency range were dependent on frequency and location of actuator but independent of the type of actuator. As long as the location of the PZT patch remained the same and its actuation capability remained, the structural modes excited would be the same. The resonance peaks' height were however reduced due to reduction in energy of actuation, probably caused by reduction in the patch's surface area.

Understanding the sensitivity of different frequency range, the identification of temperature effect, structural damage and PZT patch's damage could be conveniently achieved by simply observing the admittance signatures at different intervals.

4.7 Summary, Comments and Improvements on Issues Related to Practical Application of EMI Technique

4.7.1 Appropriate bonding thickness and working temperature

As shown in the previous sections, Bhalla (2004) recommendation's stating that the bonding thickness should preferably be smaller than one-third of the thickness of the patch was proven to be sensible throughout the series of experimental studies. A relatively thin bonding thickness ensures more effective actuation and sensing. It also minimizes the adverse effect caused by leftward shifting of the PZT resonance especially at elevated temperature. However, it should be noted that damage detection is still possible with thicker bonding though the signatures acquired might be weaker especially at high temperature and prone to contamination.

Throughout the experiments, it was discovered that thin bonding thickness could be expediently obtained on smooth and flat surface by gently squeezing the excess adhesive between the patch and the structure (before the adhesive cures) and maintaining the pressure with a dead weight during the curing of adhesive. Subsequently, a bonding film with thickness smaller than $0.05mm$ (which is less than one third of a $0.15mm$ patch) could be produced.

4.7.2 Appropriate utilization of all frequency ranges

Application of the EMI technique depends heavily on the admittance signatures at various frequencies acquired, which indirectly relates itself to the structural state of vibration. Understanding the fundamental behavior of PZT-structure interaction at different frequency range would be helpful in obtaining meaningful information for the application of the EMI

technique.

It was proven in this study that the higher range of frequency ($> 200 \text{ kHz}$), which reflects the PZT's resonances, is very useful for the identification of temperature induced deviation and damage inflicted on the PZT patch.

On the other hand, the frequency range, preferably lower than 100 kHz (up to a maximum of 200 kHz if the bonding is thin and temperature is not very high) is useful for structural damage detection.

4.7.3 Signal processing and weaknesses of conventional RMSD damage quantifier

At this point, fully automated SHM system using the EMI technique is yet to be achieved. One of the reasons is the lack of appropriate damage quantifier. The technique relies primarily on qualitative analysis.

The conventional non-parametric damage detection and quantification approaches such as root mean square deviation (RMSD) and damage index (DI) were found to be ineffective in real life SHM due to the susceptibility of the admittance signatures to external effects as described in the previous sections. The vertical shift of signatures or change in height of resonance peaks are easily affected by various external factors, including temperature, bonding, humidity and frequency step. These effects significantly affect the RMSD values measured, rendering them ambiguous.

Horizontal shift or change in modal frequency is a much better representation of the structural state and is relatively steadfast to external disturbance. Damage detection algorithm focusing on the tracking of horizontal movement of peaks ought to be developed.

CHAPTER 5 FINITE ELEMENT MODELING OF EMI TECHNIQUE

5.1 Introduction

5.1.1 Background

In engineering design, modeling of the engineering system is often vital to have a better understanding of the problem domain as well as to achieve an efficient design. As narrated in Chapter 2, various analytical based models simulating the PZT - structure interaction have been developed by previous researchers. However, analytical models are often limited in actual application because they are only applicable to simple structures such as beams, plates and shells with easy to simulate boundary conditions. Subsequent developments in various numerical methods, such as finite element method (FEM) were found to be an ideal alternative.

Research and study on the FEM in the past few decades has evolved the method into an indispensable tool in modern day for modeling and simulation of various complicated engineering systems. Historically, the FEM was first developed for solving problems involving stress analysis. It was subsequently extended to other engineering problems including thermal analysis, fluid flow analysis, piezoelectric analysis and electromagnetic analysis under steady, transient or harmonic states.

In finite element (FE) modeling, the targeted system (such as a structure) is first modeled and divided into numerous discrete elements (known as finite element) with each of them 'tied' together at their perimeters' nodes through various physical parameters depending on the requirements. This process of dividing into discrete element, commonly known as meshing is extremely useful for solving real life engineering problems which are often complex in terms of shapes, materials, boundary conditions and loadings.

From application point of view, FEM enables the analyst to numerically evaluate an approximate, but reasonable solution useful for engineering design. This is highly desirable in actual application when analytical modeling is impossible.

Existing literatures reveal that a number of approaches for establishing the FE problems

are readily available, such as direct formulation, minimum total potential energy formulation and weighted residual formulations. Solving of the systems of equations often employs the direct method and the iterative method. The complete solution can be generated by assembling the individual solutions while maintaining the continuity at the inter-elemental boundaries (Moaveni, 2003).

The outcome of the analysis, which usually involves vast amount of data, can be conveniently presented and analyzed with modern day's computer. Most commercially available software enables the display of solutions through 3D graphics with contours and colors representing the intensities of the desired outcome. Results in numerical values for nodes and elements could also be expediently acquired.

Rapid advancement of the computer's technology, especially the processing speed and graphics display capability renders the FEM an increasingly robust and indispensable tool in modern day's engineering.

5.1.2 Review on FE modeling of PZT – structure interaction

Lalande (1995) provided excellent, insight review into the FE modeling approaches for the simulation of PZT-structure interaction. They could be broadly classified into 3 categories, namely direct formulation of elements for specific application, utilization of a thermoelastic analogy and the use of commercially available FE analysis (FEA) codes incorporated with piezoelectric element formulation. Lalande (1995) attempted the dynamic FEA of ring and shell structures using commercially available software ANSYS 5.0. Good correlation was found between the FE results and results from impedance based model.

Fairweather (1998) developed a FEA-based impedance model for the prediction of structural response to induced-strain actuation. The model utilized the FEM to determine the host structure's impedance. In his model, he computed the frequency response of a structure based on eigenvalues and mass normalized eigenvectors. This operation could be performed by most commercial FE solvers. The simplicity of this model was reflected from the fact that modeling of the actuator (PZT patch) was not required as it was represented by a force or moment. The driving point mechanical impedance could be derived by evaluating the ratio of

force to velocity.

Initial applications of the abovementioned models were mainly focused on relatively low frequency of excitation, typically lower than 1 kHz . The FEA-based impedance model was later applied to the EMI technique, which involved much higher frequency of excitation, in the order of tens to hundreds of kHz.

Bhalla (2001) simulated a concrete FE model with damages incorporating 1-D FEA-based impedance model. Lim (2004) showed reasonably good comparison of mechanical impedance between experiment and 1-D FEA-based impedance model for aluminum beam, truss and concrete cube. Bhalla (2004) improved the model by incorporating 2-D effective impedance. In fact, the FEA-based impedance model was extended to a semi analytical model by incorporating the impedance based analytical model with the FE model. This model made use of the robustness of the FEM in modeling complex system while retaining the simplicity of impedance based analytical model to obtain the admittance signatures from the mechanical impedance.

At low frequency of excitation, simplification of the PZT patch into a force or moment is normally acceptable. However, at high frequency of excitation such as in the application of the EMI technique, such simplification could lead to considerable loss in accuracy. In the modeling of the EMI technique, accurate prediction of modal frequencies of the host structure is essential. Therefore, such losses in accuracy could be intolerable.

Study conducted by Makkonen (2001) showed that fairly accurate results could be obtained for dynamic harmonic problems by FEM, up to frequency of GHz range. Therefore, the ability of the FEM to predict the behavior of PZT – structure interaction system in the EMI technique should not be questioned, provided that the simulation is appropriately performed.

To the best knowledge of the author, in the field of EMI technique, no study has been conducted to simulate the PZT – structure interaction using FEM incorporating the PZT patch itself. In this study, complete modeling of PZT – structure interaction including the bonding layer using commercially available FE software, ANSYS 8.1 (ANSYS, 2004) was attempted and would be presented in the following sections. The outcomes were compared with those obtained from the impedance based analytical model as well as the experiment. This study aimed at opening a new FE modeling path in simulating PZT – structure interaction for the EMI

technique.

5.2 FE Modeling – Theory and Applications

With the help of powerful commercial FE software such as ANSYS, ABAQUS and ATILA, FE modeling and analysis process is becoming increasingly efficient with user friendly interfaces. However, it would always be very useful for the analyst to have certain level of understanding on the theoretical background of the method. This section briefly review some basic theory and concept related to the simulation of the PZT – structure smart system interaction based on commercial FE software, ANSYS 8.1.

The smart system of interest typically comprises of one or more PZT patch, acting as collocated actuator and sensor, a host structure and a layer of bonding film.

General equation of motion for a forced structural system using the Galerkin finite element discretization (Moveni, 2003) can be expressed by the following differential equation:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\} \quad (5.1)$$

where $[M]$, $[C]$ and $[K]$ are the structural mass matrix, damping matrix and stiffness matrix respectively. With $\{F\}$ denoting the applied harmonic loading, $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ indicate the nodal acceleration vector, velocity vector and displacement vector, respectively.

5.2.1 FEA-based impedance model

In FEA-based impedance model, the PZT patch is simplified to some arbitrary steady state harmonic forces applied at the ends of the patch.

$$\{F\} = \{F_0\}e^{j\omega t} \quad (5.2)$$

where F_0 denotes the magnitude of the force, j is the imaginary number, ω is the angular frequency and t for time.

All the frequency dependent parameters will follow the applied frequency, though not necessarily in phase due to the presence of damping. The resulting displacement could then be defined as:

$$\{u\} = \{u_0 e^{j\phi}\} e^{j\omega t} \quad (5.3)$$

with ϕ representing the displacement phase shift (phase angle).

The displacement could be expressed in a more convenient form, which is the usual output of commercial FE software:

$$\{u\} = \{\{u_1\} + j\{u_2\}\} e^{j\omega t} \quad (5.4)$$

where $\{u_1\}$ and $\{u_2\}$ denote the real and imaginary displacement vector respectively.

Taking the 1-D case as an example, two equal and opposite forces are normally applied at both ends of the patch. Performing the numerical analysis (say using ANSYS), the resulting displacement, u is readily available at both loading points. Thus the drive point mechanical impedance (at one of the loading points) can be conveniently evaluated as:

$$Z = \frac{F}{\dot{u}} \quad (5.5)$$

where the velocity, $\dot{u}$ can be derived by differentiating the displacement:

$$\dot{u} = j\omega u$$

Similar concepts have been applied to 2-D structures by Bhalla (2004).

For EMI technique applications, the mechanical impedance obtained could be converted to admittance signature as if it is measured by impedance analyzer, through the impedance based electromechanical coupling equation (Liang et al., 1999; Bhalla, 2004).

5.2.2 Inclusion of induced strain actuator in FE model

A number of commercially available software offer piezoelectric analysis which allows the modeling of PZT – structure interaction to include the induced strain actuator (PZT patch). ANSYS version 8.1 was adopted in this study; hence all the following sections referred to ANSYS (2004).

In ANSYS version 8.1, piezoelectric analysis comes under the category of coupled field analysis. Coupled field analysis considers the interaction or coupling between two or more disciplines of engineering (ANSYS, 2004). Piezoelectric analysis caters for the interaction between structural and electric fields. Static, modal, harmonic and transient analyses could be

performed. Other coupled field analyses include thermal-stress, fluid structure, magnetic-thermal, magneto-structural and micro-electromechanical (MEMS).

Coupled field analysis derives solutions to problems not possible with the usual FEM, by simplifying the modeling of coupled-field problems. However, this leads other problems like increased wavefront, inefficient matrix reformulation and large storage requirement.

Piezoelectric analysis makes use of direct coupling method, which involves just one analysis with the use of one coupled-field element containing all necessary degrees of freedom. The FE formulation used for developing the matrix equations is the strong coupling method (ANSYS, 2004):

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} \quad (5.6)$$

where X_1 and X_2 are two different types of degrees of freedom. The coupled effect is taken into account by the off-diagonal sub-matrices $[K_{12}]$ and $[K_{21}]$. Using this method, coupled response could be obtained after one iteration.

With the linear electromechanical constitutive equations (Equation 2.11) incorporated into Equation 5.1, the FE discretization can be performed by establishing nodal solution variables and element shape functions over an element domain, in which the solution could be approximated. With the application of variational principle and FE discretization, the coupled FE matrix for one element model can be expressed as (ANSYS, 2004):

$$\begin{bmatrix} [M] & [0] \\ [0] & [0] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}\} \\ \{\ddot{V}\} \end{Bmatrix} + \begin{bmatrix} [C] & [0] \\ [0] & [0] \end{bmatrix} \begin{Bmatrix} \{\dot{u}\} \\ \{\dot{V}\} \end{Bmatrix} + \begin{bmatrix} [K] & [K^z] \\ [K^z]^T & [K^d] \end{bmatrix} \begin{Bmatrix} \{u\} \\ \{V\} \end{Bmatrix} = \begin{Bmatrix} \{F\} \\ \{L\} \end{Bmatrix} \quad (5.7)$$

in which $\{V\}$ is the vector of nodal electric potential where the dot above variables denotes time derivative, $\{L\}$ is the vector of nodal, surface and body charges, $[K^z]$ is the piezoelectric coupling matrix and $[K^d]$ is the dielectric conductivity.

This formulation is very convenient for evaluating the admittance signatures as if it is measured by the impedance analyzer in the EMI technique. The complex admittance signature, which is the ratio of electric current to voltage, can be expressed as:

$$\bar{Y} = \frac{\bar{I}}{\bar{V}} \quad (5.8)$$

where $\bar{V}$ is the voltage applied by impedance analyzer and $\bar{I}$ is the modulated current, with the dashes above the variables indicating complex terms.

The complete modeling technique which includes the PZT patch and preferably, the bonding layer should yield a more accurate result especially at high frequency of excitation. Moreover, the outcome acquired, which is the electric current can be directly compared with the admittance signature from the EMI technique. This saves all the hassle of converting the mechanical impedance into electrical admittance through the impedance based electromechanical coupling equation as required in the FEA-based impedance model.

5.2.3 Modeling of structural damping

The effect of damping is inevitable in structure under vibration. For harmonic analysis, the structural damping matrix could be generally expressed in terms of the stiffness and mass matrix as:

$$[C] = \alpha[M] + \beta[K] + \sum_{j=1}^{NMAT} \beta_j [K_j] \quad (5.9)$$

where α is the constant mass matrix multiplier, β is the constant stiffness matrix multiplier, NMAT indicates the number of materials with damping input in the analysis, β_j is the constant stiffness multiplier for material j and K_j is the portion of structure stiffness matrix based on material j . This type of damping is in general known as Rayleigh damping.

Due to the nature of damping which is uncertain, predicting the various parameters listed above is not straightforward and depends heavily on experience. Trial and error is also often required. In this study, $\alpha = 0$ and $\beta = 3 \times 10^{-9}$ were adopted according to the recommendation by Bhalla (2004). It should be mentioned that the β value was an average as it often needed to be adjusted through trial and error to fit the experimental results. However, the variation should not be too large ($1 \times 10^{-9} < \beta < 6 \times 10^{-9}$).

5.3 Modeling and Analysis Using ANSYS 8.1

The entire process of modeling and analysis comprises of three stages, namely the pre-processing phase, solution phase and post-processing phase. In the pre-processing phase, the element types have to be selected and material properties inserted. After which the geometrical shapes of the model is built up. The model is then discretized (meshed) into a number of finite elements with element's attributes and material properties assigned accordingly. At this stage, loadings and boundary conditions are to be applied on the elements, nodes, surface area or volume depending on the problem. The final step is the selection of the type of analysis. In this study, harmonic analysis is performed. Normally, a full analysis is preferred for solution with higher accuracy.

At the solution phase, a set of linear or non-linear algebraic equations is solved simultaneously to obtain the nodal solutions, such as displacement and electric current. Post-processing is a phase where the analyst acquires the desired information either in data or graphical form.

5.3.1 FE modeling of freely suspended PZT patch

In order to have a better understanding of the piezoelectric analysis, modeling of the PZT patch was first performed without the presence of the host structure. ANSYS 8.1 possesses a number of elements that could accommodate piezoelectric properties, such as Plane 13 for 2-D analysis and Solid 5, Solid 226 for 3-D piezoelectric analysis.

In this study, 3-D modeling is performed with the use of both Solid 5 and Solid 226 elements. Solid 5 element is a coupled field solid with eight nodes and up to six degree of freedom at each node. Solid 226, on the other hand, has 20 nodes with up to four degrees of freedom per node.

The excitation of the PZT patch in this study was well within the linear range. Effect of hysteresis was also assumed to be negligible due to the use of relatively thin and small patch with low voltage of excitation.

A freely suspended PZT patch dimensioned $10\text{mm} \times 10\text{mm} \times 0.3\text{mm}$ was modeled in

ANSYS 8.1 workspace as depicted schematically in Figure 5.1. The material properties, in accordance to PIC 151 (PI Ceramic, 2006) were assigned to the PZT patch as tabulated in Table 5.1.

An alternating voltage with $1V$ in magnitude was applied across the patch for excitation along the Z direction. It should be noted that, due to the symmetrical nature of both geometrical shapes and loadings, only one-fourth of the patch is modeled. With this, the interfacial nodes along the x -plane were restrained in the x -direction and those along the y -plane were restrained in the y -direction as shown in Figure 5.1. It should also be noted that the system is symmetrical, in terms of geometry and boundary conditions along the x -plane and y -plane. One node at the center of the patch (at the lower left edge of the one-fourth patch) was also restrained in the Z -direction to maintain the stability of the patch. It should be noted that the x -plane and y -plane are the symmetrical planes of the PZT patch.

Figure 5.1: Isometric view of one-fourth of PZT patch modeled in ANSYS 8.1 workspace.

Convergence of the solutions was tested in two ways. Firstly, according to the

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recommendation by Makkonen (2001), to ensure sufficient accuracy to the solution, the size of the element should typically lie between three to five nodal points (two to three elements) per half wavelength for harmonic analysis. In this case, the half wavelength estimated through the wave number (reciprocal of wavelength), assuming the highest frequency – 1000 kHz , was approximately 0.24 mm . However, the smallest element achievable (considering the time consumption and processing capability of the computer) in this analysis is 0.2 mm , which is nearly twice of the minimum requirement. Conversely, with 0.2 mm mesh as the smallest element size, the maximum frequency allowable is 610 kHz . The detailed calculations are attached in Appendix C.

On the other hand, convergence was also tested by performing several analyses with reduction in the elements' size for each analysis. At the first instance, a loose frequency step (5 kHz) was adopted. Subsequent frequency steps ranged from 1 kHz to 10 kHz depending on the locations of the resonance peaks were used. Frequency range with resonance peaks were allocated with closer steps.

Table 5.1: Piezoelectric properties of PIC 151 (PI Ceramics, 2006).

Parameters	Symbols	Values	Unit
Density	ρ	7800	kg/m^3
Dielectric loss factor	$\tan \delta$	0.02	--
Compliance	s_{11}	15.0	$\times 10^{-12} m^2/N$
	$s_{22} = s_{33}$	19.0	
	$s_{12} = s_{21}$	-4.50	
	$s_{13} = s_{31}$	-5.70	
	$s_{23} = s_{32}$	-5.70	
	$s_{44} = s_{55}$	39.0	
	s_{66}	49.4	
Electric Permittivity	ϵ_{11}^T	1.75	$\times 10^{-8} F/m$
	ϵ_{22}^T	1.75	
	ϵ_{33}^T	2.12	
Piezoelectric Strain Coefficients	d_{31}	-2.10	$\times 10^{-10} m/V$ or $\times 10^{-10} C/N$
	d_{32}	-2.10	
	d_{33}	5.00	
	d_{24}	5.80	
	d_{15}	5.80	

Convergence was reached at Solid 5 element sized $0.2mm$ and Solid 226 element sized $0.5mm$ even at very high frequency (such as the resonance peak near to 800 kHz), as illustrated in Figure 5.2.

Thus, it could be deduced that element sized $1mm$ or $0.5mm$ using Solid 5 element would be sufficiently fine for the modeling of PZT - structure interaction in the EMI technique, which normally would not exceed 200 kHz . In actual application, element size as small as $0.2mm$ is not recommended as it requires intensive computation which can be extremely time consuming, especially with the present of the host structure. With a personal computer of model Pentium 4 ($3.0GHz$ processing speed), the computational time of model using Solid

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226 with 0.5mm element consumed approximately half an hour depending on various given conditions.

Figure 5.2: Admittance signatures against frequency plot for numerically simulated PZT patch (free-ended) with different element sizes between 0 - 1000 kHz.

(a) Conductance signatures (real component)

(b) Susceptance signatures (imaginary component)

5.4 Comparison with Existing Impedance-Based Analytical Model and Experiment

In this section, outcome from analytical model and experimental test were compared with the obtained numerical results. This study provides a preliminary investigation into the feasibility of FE model incorporating the PZT patch for the simulation of the EMI technique.

5.4.1 Analytical modeling of free-ended PZT patch

Analytical model of the free-ended PZT patch can be conveniently obtained by setting the mechanical impedance of the host structure, Z to zero in the impedance based electromechanical coupling equations (section 2.8.1).

For the 1-D free PZT patch model (Equation 2.18), the impedance based electromechanical coupling equation (Liang et al., 1994) can be reduced to:

$$\bar{Y} = 2\omega j \frac{wl}{h} \left[\bar{\epsilon}_{33}^T + d_{31}^2 \bar{Y}_{11}^E \left(\frac{\tan \kappa l}{\kappa l} - 1 \right) \right] \quad (5.10)$$

Rearranging the terms and expressing them in terms of real and imaginary components:

$$\bar{Y} = \left\{ -4\pi f \frac{wl}{h} \left[d_{31}^2 Y_{11}^E (t + \eta(r-1) - \delta \epsilon_{33}^T) \right] \right\} + j \left\{ 4\pi f \frac{wl}{h} \left[\epsilon_{33}^T + d_{31}^2 Y_{11}^E (r - \eta t - 1) \right] \right\} \quad (5.11)$$

where $r + tj = \frac{\tan \kappa l}{\kappa l}$, $\bar{Y}_{11}^E = Y_{11}^E (1 + \eta j)$, $\bar{\epsilon}_{33}^T = \epsilon_{33}^T (1 - \delta j)$ with δ and η indicating the electrical loss factor and mechanical loss factor respectively. A simple program code written in Matlab 6.5 (Palm, 2001) was used to evaluate the electrical admittance against different frequency as attached in Appendix D.

In the case of 2-D model based on cross impedance using the equation proposed by Zhou et al. (1995), free PZT vibration could be modeled by setting all 4 terms related to structural mechanical impedance to zero. Equation 2.20 and Equation 2.21 can thus be reduced to:

$$\bar{Y} = 4j\omega \frac{wl}{h} \left[\bar{\epsilon}_{33}^T - \frac{2d_{31}^2 \bar{Y}^E}{(1-\nu)} + \frac{d_{31}^2 \bar{Y}^E}{(1-\nu)} \left\{ \frac{\sin \kappa l}{l} \quad \frac{\sin \kappa w}{w} \right\} \begin{bmatrix} \kappa \cos \kappa l & 0 \\ 0 & \kappa \cos \kappa w \end{bmatrix}^{-1} \right] \quad (5.12)$$

Again, rearranging and expressing in complex notations:

$$\bar{Y} = 8\pi f \frac{wl}{h} \left\{ \left[\varepsilon_{33}^T \delta - \frac{d_{31}^2 Y^E}{(1-\nu)} (t + T + \eta(r + R - 2)) \right] + j \left[\varepsilon_{33}^T + \frac{d_{31}^2 Y^E}{(1-\nu)} [r + R - \eta(t + T) - 2] \right] \right\} \quad (5.13)$$

where $R + Tj = \frac{\tan \kappa w}{\kappa w}$.

Similarly, setting the effective structural impedance to zero in the 2-D effective impedance modeling equation (Equation 2.22) (Bhalla, 2004) yields:

$$\bar{Y} = 4\omega j \frac{l^2}{h} \left[\frac{\varepsilon_{33}^T}{\varepsilon_{33}} + \frac{2d_{31}^2 \bar{Y}^E}{(1-\nu)} \left(\frac{\tan \kappa l}{\kappa l} - 1 \right) \right] \quad (5.14)$$

Again, rearranging and expressing in complex notations:

$$\bar{Y} = 8\pi f \frac{l^2}{h} \left\{ \left[\delta \varepsilon_{33}^T - N(t + \eta r - \eta) \right] + j \left[\varepsilon_{33}^T + N(r - \eta t - 1) \right] \right\} \quad (5.15)$$

where $N = \frac{2d_{31}^2 Y^E}{(1-\nu)}$. Appendix D listed the program codes written in Matlab 6.5 for the derivation of admittance signatures against frequency for both Equation 5.13 and Equation 5.15.

5.4.2 Experiment on free-ended PZT patch

Admittance signatures of two freely-suspended PZT patches ($10\text{mm} \times 10\text{mm} \times 0.3\text{mm}$) as shown in Figure 4.1(e) were acquired using the impedance analyzer. The free ended boundary condition was simulated by suspending the patches in air using the two soldered wires. As both patches possessed almost identical admittance signatures plot, only one of the signatures was used for comparison in the following sections.

5.4.3 Results and discussions

The admittance signatures obtained analytically, numerically and experimentally from a free-ended PZT patch are compared in Figure 5.3. The numerical results were obtained from analysis using Solid 226 element with a mesh size of $0.5mm$ and $\beta = 3 \times 10^{-9}$. On the other hand, it was discovered that the analytical outcome of the 2-D model based on cross impedance and effective impedance yield exactly the same results and thus only one of it is plotted, representing both.

A glance at Figure 5.3 suggests that both the numerical and analytical modeling provided reasonably good predictions on the actual vibrational behavior (experiment) of the PZT patch as the major resonance peaks were well predicted. The susceptance plot exhibits similar outcome, as attached in Appendix E.

Figure 5.3: Conductance signatures against frequency plot for free ended PZT patch.

- (a) Experimental vs. numerical (100 – 900 kHz)
- (b) Experimental vs. analytical (100 – 900 kHz)
- (c) Experimental vs. analytical (100 – 600 kHz)

However, a close up into frequency range between 100 – 600 kHz suggests that the analytical models were unable to predict two resonance peaks and a twin peak as depicted in Figure 5.3 (c). Bhalla (2004) attributed these phenomenons to the deviation in the shape of the PZT patch from perfect square during manufacturing and edge roughness induced secondary vibration. In short, he attributed the inaccuracy to the manufacturing inaccuracy.

On the other hand, these peaks could be predicted by the numerical model as plotted in Figure 5.3 (a). Both twin peaks and two smaller resonance peaks were successfully simulated in the numerical model. This indicates that they were not caused by manufacturing error but reflected the shortcoming of the analytical models. This is conceivable due to oversimplification of the analytical models. At high frequency of excitation, simplification of the motion into points or perimeter interactions led to erroneous results.

This outcome proved the robustness and capability of ANSYS 8.1 in simulating dynamic motion of PZT patch under high frequency of excitation. With this, the PZT-structure interaction is studied and presented in the later sections.

From Figure 5.3 (a), it could be seen that the modal frequencies predicted numerically

were generally larger than those obtained from the experiment. According to the structural dynamics theory, horizontal movement of peaks (modal frequency variation) was mainly caused by changes in stiffness. It is well known that the stiffness depends largely on strain rate and amount of strain. The value provided by the manufacturer was just an average which may not be representative in the case of high frequency of actuation which has very high and changing strain rate, and with very small strain. Minor adjustment thus was performed by reducing the overall stiffness (Young's modulus) by 7% and a much better matching was obtained, as plotted in Figure 5.4.

Figure 5.4: Conductance signatures against frequency plot (100 – 900 kHz) with overall PZT patch's stiffness reduced by 7%.

With the adjusted stiffness, another numerical model was built based on PZT patch sized $15\text{mm} \times 15\text{mm} \times 0.5\text{mm}$ under similar free-ended condition. Comparing with the signatures obtained from the experiment, as shown in Figure 5.4, very good match was achieved even for minor peaks. Both cases showed that the adjusted stiffness is applicable for frequency range less than about 600 kHz , above which accuracy decreases.

Figure 5.5: Comparison of conductance signatures against frequency plot (0 – 1000 kHz) between experimental test and numerical model for PZT patch dimensioned 15mm x 15mm x 0.5mm.

Despite the higher accuracy in predicting the resonance peaks, one limitation of the numerical model is reflected in the above figures where the predicted peaks' magnitudes differ significantly from the experiment. Adjustment of peaks height was very difficult as it depends heavily on trial and error of different parameters such as damping ratio. Excessive trials and errors performed for obtaining a suitable damping value with very small frequency step could be uneconomical. A balance between accuracy and time consumed is essential.

5.5 FE Modeling of PZT - Structure Interaction

The previous sections demonstrated the robustness of the FEM for modeling of PZT patch under harmonic excitation up to 1000 kHz. In this section, the FEM was extended to the simulation of PZT-structure interaction, inclusive of the interfacial adhesive layer.

In the subsequent sections, all the PZT patches were modeled with Solid 5 elements instead of Solid 226. This is due to the fact that Solid 5 element possesses lesser nodes which is more convenient in modeling multiple structures interactions. In addition, according to recommendation by ANSYS (2004), a smaller size element with lesser nodes is preferred over a larger size element with more nodes.

5.5.1 Simple beam

A simple rectangular aluminum beam sized $231\text{mm} \times 21\text{mm} \times 2\text{mm}$ was used as the test specimen in this study. A $10\text{mm} \times 10\text{mm} \times 0.2\text{mm}$ PZT patch was bonded at the middle of the beam. Additionally, a similar model was numerically simulated in the ANSYS 8.1 workspace as illustrated in Figure 5.6. To be more realistic, the bonding layer (0.03mm) was also simulated. Again, taking advantage of the geometrical and loading symmetry, only one-fourth of the system was simulated.

The Young's modulus and the Poisson ratio of the bonding layer was taken as $5.1 \times 10^9 \text{ N/m}^2$ and 0.4 respectively, as recommended by Ong (2003). The damping of the bonding (6.0×10^{-9}) was also adjusted to be about 6 times larger than that of the aluminum (1.0×10^{-9}). The material properties of the aluminum beam and adhesive are listed in Table 5.2.

The type of element used for both bonding layer and aluminum beam is Solid 45, specified for modeling of solid structures with eight nodes and three degree of freedom at each node. It is worth mentioning that the patch was simulated to be 'bonded' to the aluminum beam through the bonding layer by merging the interfacial nodes between the patch and the bonding layer as well as between the structure and the bonding layer. Merging of the nodes ensured that the interfacial nodes carried the same displacements and thus ensuring strain transfer.

Both planes of the bonding layer in the Z-direction (interacting with the structure and the PZT patch) were assumed to be horizontal and in parallel to each other. In other words, the PZT patch was assumed to be in parallel to the structure. This is justifiable because during the preparation of the actual specimen, uniform pressure was applied across the patch ensuring tight contact with the structure's flat surface throughout the process of curing of the adhesive.

Element sized 0.5mm was adopted throughout the entire structure. Total numbers of elements generated were 2048. According to Makkonen (2001) recommendation, an element size of 0.7mm will be sufficient for this model, which has a maximum frequency of 200 kHz (calculation attached in Appendix C). Using the same computing facility as mentioned previously, the computational time was approximately 3 hours.

Figure 5.6: Isometric view of one-fourth of aluminum beam (231mm x 21mm x 2mm) bonded with PZT patch modeled in ANSYS 8.1 workspace.

Table 5.2: Material properties for aluminum beam and adhesive.

Parameters	Symbols	Materials	Values	Unit
Density	ρ	Aluminum	2715	kg/m^3
		Epoxy	1000	
Poisson ratio	ν	Aluminum	0.3	--
		Epoxy	0.4	
Young's modulus (Isotropic)	Y	Aluminum	5.1	$\times 10^9 N/m^2$
		Epoxy	68.95	
Constant stiffness multiplier	β	Aluminum	1×10^{-9}	--
		Epoxy	6×10^{-9}	

The numerical outcome was compared against the experimental results in Figure 5.7 for two different frequency ranges. From the figure, it could be concluded that the simulation is successful, as shown from the good matching of the slope of curve, modal frequencies and peaks' magnitudes, even up to frequency as high as 100 kHz.

In comparison with other models in the field of EMI technique, this numerical model exhibited exceptional robustness. For instance, most of the models previously studied by other researchers, either purely analytical through impedance-based modeling or semi-analytical through FEA-based impedance modeling, were often unable to model the minor peaks (Zagrai and Giurgiutiu, 2001), exhibited large variation in magnitudes (Lim, 2004, Giurgiutiu and Zagrai, 2000) and showed low accuracy when frequency range exceeded 60 kHz (Ong, 2003).

These shortcomings are attributed to a number of reasons. Firstly, at high frequency of excitation, numbers of modes of the vibrating structure are numerous and complicated. Under such context, the FEA-based impedance modeling which converts the actuator (PZT patch) into a force or moment could be oversimplified. The full FE model incorporating the PZT patch simulates the whole finite area beneath the patch, instead of simplified end points interaction in the FEA-based analytical modeling. Some of the vibrational modes may not be triggered and

thus their modal frequency may not be accurately predicted.

Secondly, the basic assumption which neglects the effect of bonding (ideal bonding) is not realistic at high frequency due to highly localized actuation. The effect of shear lag is usually not negligible unless the bonding film is sufficiently thin, as described in the previous chapter. Some researchers (Ong, 2003, Xu and Liu, 2003 and Bhalla, 2004) have introduced modification to the impedance based electromechanical coupling equation (Liang, 1994 and Bhalla, 2004) by incorporating the effect of bonding. All these problems are negligible at low frequency of actuation.

Figure 5.7: Comparison of admittance signatures against frequency plot between experimental test and numerical model for aluminum beam specimen (231mm x 21mm x 2mm).

- (a) Numerically obtained conductance signatures (35 – 60 kHz)
- (b) Experimentally obtained conductance signatures (35 – 60 kHz)
- (c) Numerically obtained susceptance signatures (80 – 100 kHz)
- (d) Experimentally obtained susceptance signatures (80 – 100 kHz)

5.5.1.1 Modeling of bonding film

One of the inherent advantages exhibited by the FEM in the modeling of PZT-structure interaction could be its ability to physically model the bonding film, which is essential in strain transfer. This section presents a numerical study investigating the effect of bonding thickness on the admittance signatures acquired from PZT patch bonded on structure. The numerical results are verified experimentally.

A lab-sized, rectangular aluminum beam (50mm x 21mm x 2mm) with its properties same as the previous sample was chosen with a PZT patch (10mm x 10mm x 0.3mm) bonded at the

middle of the beam. In this case, a small beam was purposely selected to reduce the computational time, as the frequency involved was relatively wide, ranging from 0 to 1000 kHz. Same type of element and material properties as described in the previous section were reused.

The actual bonding thickness was measured to be 0.03mm. Numerical model, incorporating this bonding thickness was generated and analyzed in ANSYS 8.1 workspace. The outcome of analysis was compared with the experimental results in Figure 5.8.

The admittance signatures plot indicates that those structural peaks below 500 kHz and the two PZT peaks occurring at 600 kHz and 850 kHz were well simulated by the model. This outcome again shows that the overall vibrational behavior of the smart system was well simulated through FEM up to a frequency of 1000 kHz.

Figure 5.8: Comparison of conductance signatures against frequency plot (0 – 1000 kHz) between experimental test and numerical model for aluminum beam specimen dimensioned 50mm x 21mm x 2mm.
(a) Numerical
(b) Experimental

Models with different bonding thicknesses were further simulated and analyzed. The admittance signatures were plotted against frequency, as illustrated in Figure 5.9. From Figure 5.9 (a), the progressive leftward shift of PZT peaks with increasing bonding thickness indicates the increasingly dominating PZT patch's resonances. This is attributed to the shear lag effect, which worsens with increasing bonding thickness, resulting in weaker PZT-structure interactions. However, at moderate frequency of excitation, increase in bonding thickness did not affect the modal frequency of the structural resonance (Figure 5.9b). Only the peaks' magnitudes were affected by the change in bonding thickness but did not show any systematic

trend with the change.

This is a general observation for various peaks at frequency lower than *200 kHz*. In fact, the numerical results agreed very well with the experimental observations presented in Chapter 4. Therefore, it could be inferred that at moderate frequency range, the modal frequencies are insignificantly affected by the bonding thickness. However, the adverse effect of bonding on overall magnitudes of signatures caused by leftward shift of PZT peaks was inevitable when bonding thickness is *0.2mm* (larger than one-third of the PZT patch's thickness). Above *200 kHz*, the domination of PZT peaks rendered the signatures more susceptible to changes, such as due to temperature variation. Therefore, at moderate frequency of excitation, the assumption of neglecting the effect of bonding is acceptable if the peaks' magnitudes are not the major concern but the modal frequencies.

The recommendation provided in the previous chapter where the frequency used in the EMI technique should not exceed *200 kHz* was again verified – below which the bonding effect would not affect the structural peaks significantly, above which the PZT peaks dominate.

It is worth mentioning that all these observations and conclusions are general but the frequency range recommended may not be exact as different sizes of PZT patches would have different resonances. No matter how, this study shows that the FEM appears to be an excellent alternative to the experiment in evaluating the suitable range of frequency for the application of EMI technique for different sizes of PZT patches with different bonding thickness.

Figure 5.9: Conductance signatures against frequency plot acquired from numerically simulated surface-bonded PZT patch with varying bonding thickness on aluminum beam specimen (50mm x 21mm x 2mm).
(a) 0 – 1000 kHz
(b) 40 – 60 kHz

5.5.2 Modeling of more complex shapes

Besides the ability to realistically simulate the bonding film, the FE simulation possesses another inherent advantage over the analytical model, which is the ability to simulate irregular shapes with complicated boundary conditions, normally impossible to have closed form solution. This section reports the feasibility of simulating an L-shaped aluminum beam ($l = 200\text{mm}$, $w = 20\text{mm}$, $t = 1\text{mm}$) of identical properties as previous specimens with surface bonded PZT patch ($10\text{mm} \times 10\text{mm} \times 0.3\text{mm}$) at its inner center, as depicted schematically in Figure 5.10.

The numerically analyzed admittance signatures were compared with the experimentally acquired signatures from an equal size L-shaped aluminum beam. The outcome is presented in Figure 5.11.

Figure 5.10: Isometric view of one-half of an free-ended L-shaped aluminum angle ($l = 200\text{mm}$, $w = 20\text{mm}$, $t = 1\text{mm}$) bonded with PZT patch modeled in ANSYS 8.1 workspace.

In this case, reasonable accuracy between the two was achieved as most of the resonance peaks were predicted. This outcome once again demonstrated the robustness of FEM in simulating PZT-structure interaction.

However, the matching of resonance peaks was not as accurate as in the previous case on simple beam. One of the reasons could be due to some distortion on the L-shaped beam, from its ideal shape, caused by imperfect hand cutting during the preparation of the specimen. Previous specimens were machine cut by the manufacturer. Another reason could be the nature of the specimen having more complex shapes resulting in more complicated mode shapes during vibration. The presence of numerous local peaks could not be fully simulated by FEM unless a very accurate model is simulated or more perfect specimen is prepared.

Figure 5.11: Comparison of conductance signatures against frequency plot between numerical and experimental results of a PZT patch surface-bonded on aluminum beam specimen (50mm x 21mm x 2mm).
(a) Numerical
(b) Experimental

5.6 Discussions and Concluding Remarks

This chapter investigated the feasibility of performing numerical simulation on the dynamic PZT-structure interaction in the field of EMI technique using commercial FE software, ANSYS version 8.1. Investigation commenced with the modeling of free-ended PZT patch. The numerical outcome was compared with various existing impedance-based analytical models as well as with the experimental tests. More models were built in the later stage with PZT patch surface bonded on lab-sized aluminum structures of different sizes and shapes. Results were again compared with the experimental counterparts.

The FEM was proven to be a robust tool in the modeling of dynamic interactions between the structure and PZT patch at various frequency ranges, as high as 1000 kHz . Both structural and PZT patch's resonance peaks were accurately predicted. Some of the minor peaks unpredictable in impedance-based analytical models could be well simulated in the FE model. Advantages over existing FEA-based impedance modeling were also witnessed where the full FEM model incorporating the patch and the bonding simulated the actual PZT-structure interaction more realistically, especially at high frequency of excitation (kHz range).

The effect of bonding thickness was easily incorporated in the model by adding an additional layer. In this way, the effect of shear lag was also implicitly considered. Study on bonding layer was found to agree well with the experimental observations discussed in Chapter 4. Modeling of structures with complicated shapes and varying boundary conditions as well as loadings was made possible with the use of FEM.

In addition, the full FE model incorporating the PZT patch enabled direct acquisition of admittance signatures as if it were measured using an actual impedance analyzer. This considerably reduced the hassle of first obtaining the mechanical impedance and subsequently derived the admittance signatures through electromechanical coupling equation in the FEA-based impedance model.

However, shortcomings existed in spite of the advantages stated above. For instance, the use of FEM reduced the physical insight and fundamental understanding of the PZT-structure interactions, which is a general limitation of FEM. The process of simulation was tedious,

time consuming and prone to error for the inexperienced analysts. The process of analysis also required intolerable long period of time for complex structure, especially when high accuracy is necessitated. The scenario could deteriorate when large frequency range with small intervals is compulsory. Modeling of interaction between the PZT patch, bonding and structure could pose considerable difficulty under certain circumstances such as for curved or irregular surface. Modeling of actual boundary conditions is sometimes impossible especially at high frequency of excitations, which is prone to various uncertainties. Finally, prediction of different physical parameters, such as dynamic stiffness is also a challenging task.

This study in fact paved an alternative path to the investigation of the behavior of PZT-structure interaction in the application of the EMI technique through the use of FEM. Complex simulation unattainable through analytical model or difficult to be performed experimentally could be studied using the numerical model. For instance, investigations into the effect of different bonding conditions including imperfect, inclined, curved and low quality bonding could be achieved. Study into the sensing range of the EMI technique on the host structure, complicated boundary conditions and loadings, effect of damping, behavior of embedded PZT patch and interactions with more complex structures could also be performed with numerical simulation.

CHAPTER 6 INTEGRATED USE OF SMART MATERIALS IN SHM

6.1 Introduction

Smart materials such as piezo-impedance transducer (PZT) and optical fiber (FBG) have recently found their applications in the field of SHM. Each of them works on different fundamental principles (as described in Chapter 2) and is suitable for monitoring different aspects of the health of a structure. For instance, the EMI technique employing piezo-transducer is excellent in detecting incipient crack, debonding, local damages and monitoring of concrete curing, whereas FBG based sensor is robust in measuring static and dynamic strain, pressure and temperature. Each sensor possesses inherent advantages and disadvantages. It is envisaged that the integrated use of both smart materials may allow them to complement each other, resulting in a more robust SHM system. Incorporation of other smart materials such as SMA (Peairs, 2004b), for healing upon damaged could further lead to a real smart structure, capable in both sensing and actuating.

This chapter reports a detailed experimental study conducted to evaluate the performance of piezo-impedance transducers and FBG based strain sensors in detecting and characterizing damages as well as monitoring the strain in some rock-structures undergoing compression test.

Rock structure is a commonly encountered natural material in civil engineering. They are particularly important in the construction of cavern and tunnel which depend heavily on the strength of rock in supporting the structures. Potential applications of both sensors in detecting and characterizing damages on rocks were investigated in this study. Conventional electrical strain gauges (ESG) were also installed adjacent to the FBG based strain sensor for comparison.

6.2 Specimens Preparation and Experimental Setup

Three identical cylindrical rock specimens, all measuring 50mm in diameter and 100mm in length, cored out from the Bukit Timah granite site in Singapore were used as specimens. Specimens 1 and 2 were instrumented with two ESG sensors, two FBG sensors and one PZT patch respectively. Specimen 3 was instrumented with only one PZT patch. Two ESGs with gauge lengths of 60mm and 3mm respectively were instrumented on each specimen. Details and locations of the sensors are illustrated in Figure 6.1.

The FBG based strain gauges were manufactured by the Institute of Infocomm Research, Singapore, all having gauge length of 50mm . Two FBG sensors were required for each specimen for strain and temperature measurement respectively. As described in Chapter 2, temperature compensation is necessary to obtain accurate surface strain. The sensor measuring strain was physically bonded to the specimen's surface whereas the temperature measuring sensor was attached to the specimen but remained mechanically free. High strength epoxy adhesive RS 159-3957 (RS Components, 2006) was employed for bonding the strain measuring FBG sensor for specimen 1, and quick set epoxy adhesive RS 850-940 for specimen 2.

All PZT patches were $10\text{mm} \times 10\text{mm} \times 0.3\text{mm}$ in size, and conformed to grade PIC 151 (PI Ceramic, 2006). Figure 6.2 portrays the experimental setup for compression test and the instruments used for signature acquisitions for various sensors.

Figure 6.1: (a) ESG and FBG sensors (b) PZT patch (piezo-impedance transducer)

Figure 6.2: Experimental setup for compression test on rock structures and various instrumentations for sensors monitoring.

- (a) Compression testing machine, data logger for ESG and impedance analyzer for piezo-impedance transducers
- (b) Micron-optics interrogator for interrogation with FBG sensor

The PZT patch instrumented on the rock specimen was wired to a HP 4192A impedance analyzer (HP, 1996), which was controlled using a personal computer. The ESGs were wired to a strain recording data logger, both shown in Figure 6.2 (a). The FBG sensors were wired to a micron-optics interrogator which was controlled using a notebook computer, as shown in Figure 6.2 (b). The specimens were then compressively loaded in sequence at a rate of 330 kN/minute until the first predetermined load. It was then unloaded to zero load level at same rate. Strain readings from ESGs and FBGs were recorded both during loading and unloading, at selected intervals. At the end of each loading and unloading process, the electrical admittance signatures were acquired from the PZT patch. Maximum load for subsequent loading cycles was gradually increased with the abovementioned processes repeated until failure by crushing. All the specimens were thus failed under cyclic loading.

6.3 Loading History Retrieval by ESG and FBG Sensors

The stress-strain history of specimen 1 retrieved from 3mm ESG, 60mm ESG and FBG based strain sensors are illustrated in Figure 6.3. From this figure, it is apparent that the strain history obtained from the 60mm ESG (Figure 6.3b) is similar to the one acquired from the FBG strain sensor (Figure 6.3c) whereas the one measured from 3mm ESG (Figure 6.3a) shows different reading from the counterparts.

This is attributed to the fact that the 3mm ESG, which is $1/20$ of the length of the 60mm ESG generally measured the local surface strain at the point of attachment. The 60mm ESG and 50mm long FBG strain sensors, on the other hand, measured an average surface strain across the length and hence exhibited similar stress-strain graphs. Figure 6.4 shows a comparison between the stress-strain curve obtained from 60mm ESG and 50mm FBG strain gauge for each load cycle. The load histories matched especially well for cycles III, IV and V.

(a)

(b)

(c)

Figure 6.3: Stress-strain histories during compression of specimen 1 obtained using
(a) 3mm ESG (b) 60mm ESG (c) 50mm FBG based strain gauge

CHAPTER 6 INTEGRATED USE OF SMART MATERIALS IN SHM

Figure 6.4: Measurements of ESG (60mm) and FBG (50mm) sensor for each loading cycle during compression of specimen 1.

(a) Cycle I (b) Cycle II (c) Cycle III (d) Cycle IV (e) Cycle V

Results obtained from specimen 2 were very similar to specimen 1. The strain history retrieved by the *60mm* ESG resembled that of the *50mm* FBG, and was rather different from that for the *3mm* ESG. The load histories of *60mm* ESG and *50mm* FBG matched very well for cycles IV, V and VI. All results are presented in Appendix F. Incidentally, both the *60mm* ESG and the FBG based strain sensors failed prematurely during Cycle VI, much earlier than the failure of the specimen, which occurred during Cycle VIII.

6.4 Damage Detection and Characterization Using Piezo-Impedance

Signatures

Figure 6.5 shows the plot of conductance signatures against frequency for the PZT patch bonded to specimen 1, after each cycle of loading. The signatures were acquired in the frequency range *30 - 100 kHz* at an interval of *0.1 kHz*. ‘Load ratio’ in the figures refers to the stress imposed on the specimen divided by the ultimate stress. As shown earlier, the specimen was subjected to eight load cycles until it failed at a maximum stress of *154.3MPa* (corresponding to a load ratio = *1.0*).

Figure 6.5 shows an upward shift of the signatures and leftward shift of peaks from the baseline (load ratio = *0*) at load ratio of *0.33* and *0.66*. Abrupt change in trend and magnitude of signatures occurred at load ratio equals to *0.82*. In order to further investigate the implication of the outcome, a close up into frequency range of *90 - 100 kHz* is depicted in Figure 6.6.

According to the structural dynamic theory, modal frequencies of the resonance peaks are closely related to the health condition of the structure. Change in magnitude of resonance peaks at load ratio of *0.33* without significant alteration in the modal frequency indicates that the structural stiffness has not been significantly altered, which in turns implied that damage such as cracking has not been initiated. Change magnitude and minor leftward shift is attributed to the stress induced in the PZT patch as well as the structure (Abe et al., 2002 and Ong, 2003).

At a load ratio of *0.66*, resonance peaks were clearly distorted and even diminished

indicating a significant change in structural stiffness and vibrational mode shapes of the host structure. This implies deterioration in the structural health condition. Although no obvious crack can be observed from the surface of the specimen, it is conceived that some invisible or internal incipient cracks have been initialized. At load ratio of 0.82, serious damage has been induced in the specimen as implied by the complete change in the shape of the conductance signatures from the baseline. Cracking was clearly visible from the surface at this point. The PZT patch was broken at the failure load; hence the conductance signature could not be recorded at load ratio of 1.0.

Hence, this study shows that from the raw conductance signatures alone, it is possible to qualitatively infer the nature and magnitude of damage occurring in the host structure.

Figure 6.5: Conductance signatures against frequency plot for PZT patch bonded on specimen 1 at various loading stages.

Figure 6.6: Close up into conductance signatures against frequency plot for PZT patch on specimen 1 (90 – 100 kHz).

Figure 6.7 shows the conductance signatures of the PZT patch bonded to specimen 2. As reflected from the figure, the conductance signature underwent consistent drifts with increasing load ratio. Similar to the plot for specimen 1, the signatures underwent significant deviation at a load ratio of about 0.7. Similar observations and results can be drawn for specimen 3, as attached in Appendix F.

Robustness of the EMI technique could be seen in this experiment from a few aspects. Firstly, the admittance signature is insensitive to strain which is reflected in its slight variation at relatively low load ratio, thus avoiding false alarm. On the other hand, the EMI technique was shown to be an excellent tool in detecting cracking in host structure. This is due to the nature of the EMI technique which reflects the vibrational state of the structure. Significant change in mode shapes (as reflected in the significantly different resonance peaks) and significant deviation from baseline signatures imply major structural changes in the host structure. In the case of rock structures, this is most likely to be caused by severe cracking. This effect is clearly illustrated in all three cases.

It should also be noted that rocks are highly porous and brittle materials. Serious stress concentration can easily occur during the process of compression. Therefore, the failure of

rock is often sudden. The EMI technique, however, was proven to be an excellent tool in providing consistent early warning (during the incipient stage) to failure.

Figure 6.7: Conductance signatures against frequency plot for PZT patch bonded on specimen 2 at various loading stages.

6.5 Issues Related to Application of Piezo-Impedance Transducers and FBG Based Strain Sensors in SHM of Rock Structures

Three types of sensors were employed in this experimental study, namely the piezo-impedance transducers, the ESGs and the FBG based strain sensors. Figure 6.8 shows some close-up views of the first two specimens after failure. The PZT patches were found to remain intact and functional in specimen 2 (Figure 6.8c) and specimen 3 (not shown). The PZT patch bonded to specimen 1 broke at a load ratio of 0.826 as one of the crack line passed directly through the PZT patch, as shown in Figure 6.8 (a).

6.5.1 Piezo-impedance transducer

It was a surprise that the PZT patch was found to be able to sustain up to a relatively high strain of *2000 micro-strain*, and was able to function well even after the failure of the specimen. It is worth mentioning that the sustainability of the PZT patch under straining is due to the protection provided unintentionally by the bonding layer. The shear lag effect of the bonding film significantly reduced the strain being transferred to the patch, rendering the brittle PZT patch more sustainable. This is because the stiffness of the bonding layer was significantly lower than the patch as well as the host structure.

From the study, it was found that the quality of bonding appears to be an important issue. The bonding quality must be sufficiently high to prevent early debonding during the process of loading. Premature failure caused by loss of contact between the PZT patch and the host structure will render the transducer unserviceable before giving necessary warning for impending failure. In this study, no debonding was observed between the PZT patches and the host rock surfaces. Hence, RS 840-950 epoxy adhesive adopted in this study is recommended for bonding PZT patches on rock surface.

6.5.2 FBG based strain sensor

The FBG sensors performed well at low loads in the case of specimen 1, but failed prematurely through debonding during cycle VI (prior to failure of the 3mm ESG) in the case of specimen 2 (see Appendix F). From Figure 6.8(b) and Figure 6.8(d), it is noticed that significant debonding occurred between the rock surface and the FBG sensor which may be caused by the use of unsuitable adhesive or cracking of specimen. However, there was no visible crack on the surface of specimen 2 during the debonding at Cycle VI. Hence, more tests are needed to search for a more robust adhesive for the FBG sensors.

The 60mm long ESGs worked well until failure of specimen 1 (Figure 6.8b), but failed prematurely at a load ratio of 0.868 in the case of specimen 2. Partial debonding was noticed between the specimens and the sensors in both specimens 1 and 2, as can be seen from Figure 6.8(b) and Figure 6.8(d).

Figure 6.8 Specimens loaded to failure (end of compression test).

- (a) Specimen 1: PZT patch (b) Specimen 1: FBG and ESG
(c) Specimen 2: PZT patch (d) Specimen 2: FBG and ESG

6.6 Potential Applications of Integrated PZT-FBG Smart System in SHM of Various Structures and Materials

As described in the earlier sections, both FBG and PZT transducer possess inherent strength when applied as damage detector and quantifier in the field of SHM due to different principles of applications and physical quantities measured. FBG based strain sensor is proven to be able to yield strain measurement at least as accurate as that of ESG. Inherent advantages such as being able to multiplex multiple sensors, inert to corrosive environment, free from most chemical attack, immune to electrical interference etc. renders FBG to be a more robust sensor than the conventional ESG. This is especially true when it is applied at the construction site which is prone to harsh environment and various interferences.

On the other hand, inherent limitations of FBG based sensor such as mere strain measurement may not provide sufficient information regarding the health of a structure. This is due to the fact that although damage usually comes along with induced strain, it is not necessarily so. However, this can be complemented by the EMI technique, which is robust in detecting local damage, such as cracking.

This study opens a path to the integrated use of both sensors for detecting different types of damages, complementing each others, thus forming a more robust system for SHM. With the inherent robustness of respective sensors, potential real-life applications and future research directions are summarized and discussed in the following sections.

6.6.1 Application on brittle materials

Use of brittle materials, such as concrete and rock in the field of civil engineering is very common. When health monitoring is to be performed on such materials, the EMI technique plays a vital role. Brittle materials fail at relatively low strain but often accompanied by considerable cracking. Incipient cracks are often hard to predict through strain reading and are sometimes unnoticeable through visual inspection. The EMI technique, in this case, is a very good indicator of cracking; even in its incipient state, thus providing useful alarm for inspections and early repairs. On the other hand, other types of failures such as punching

failure, corrosion and other failure which are not accompanied by strain, but would lead to a change in structural mode shape (locally or globally), could be well detected by the EMI technique.

In this case, the FBG sensors would act as a complement in the health monitoring system. For instance, any significant changes in admittance signatures from the EMI technique would prompt the inspecting engineer to also check the FBG strain reading. With different amount of strain (compressive or tensile or even negligible amount) could allow the engineer to infer the type of potential failures and thus taking necessary actions. In short, the EMI technique dominates in this case due to the nature of damage in brittle materials.

6.6.2 Application on ductile materials

Ductile materials such as steel and aluminum are also often used in civil engineering structures either as main structural members or as reinforcement in composites. Being ductile in nature, the failure modes of these materials are often governed by excessive straining. In this case, FBG based strain sensor would be dominant in monitoring the structural health. Metals usually undergo large amount of straining before failure, which can be easily picked up by the FBG sensors. The EMI technique in this case is a complement as straining usually does not cause significant changes to the structural mode shapes but some uniform shift in admittance signatures. The EMI technique could complement the FBG sensors in the monitoring of metallic structures as it could be useful in detecting failures at connections and joints such as loosening of bolts, cracking of welds and other structural connections failures. Weakening of the structural connections would lead to potential failure but may not be reflected by the FBG's strain reading.

6.6.3 Issues in application of PZT-FBG smart system

In actual application, issues such as placement locations, quality of bonding, and protection of the sensors are vital to ensure optimum performance of the techniques.

In general, Bhalla and Soh (2003) recommended that the PZT patches should be placed

at locations that are prone to shear and bending failure. This suggestion is reasonable but it should be noted that the patches should be placed near to these areas instead of exactly on them so as to prevent premature failure of the patches such as the one described in the case of specimen 1. Premature failure could lead to ambiguity. The inspector may not be able to justify whether the failure is on the PZT patch or the structure.

Also, during the monitoring of a large structure, the patches should avoid locations where considerable straining is expected. Besides the abovementioned possible premature failure, avoiding stressed area would also reduce contamination of the measured admittance signatures caused by stressing. For instance, the patches should be placed along the neutral axis of a bending beam, near to connections of structural members, near to critical structural members etc. The FBG sensor, in contrary, should be placed in highly strained areas so as to pick up any strain. Further investigations should focus on setting more detailed guidelines for placement locations of respective sensors.

Other important issues would be the bonding quality and protection of the sensors in real life monitoring. A high bonding quality is not only necessary to reduce the risk of premature failure but also to ensure good contact for long term monitoring, as discussed in Chapter 2. The bonding layer should be able to resist fluctuating temperature, humidity and chemical attack. Suitable protection to shield the sensors from damages while not causing any physical obstruction or sacrificing the structural aesthetic is also necessitating more studies.

More importantly, the cost involved in using both sensors in the monitoring of large scale structures ought to be justified against the advantages before real life application is possible.

CHAPTER 7 CONCLUSIONS AND FUTURE WORKS

7.1 Introduction

Structural health monitoring employing smart materials has attracted considerable attention in the field of civil engineering. Potential applications of smart materials such as the EMI technique employing piezo-impedance transducer (piezoceramics, PZT) and strain sensing using optical fiber (Fiber Bragg Grating, FBG) in replacing the traditional SHM techniques, especially visual inspection may not only reduce the cost and manpower involved but also enable a more reliable real-time, remote and autonomous monitoring system.

The main objective of this research is to push forward the potential real-life application of the EMI technique. Various issues related to the actual applications including consistency of signatures for long term monitoring, protection of the smart sensors, environmental effects, temperature effect and bonding effect were investigated. The studies conducted on these topics were mainly based on experiments and were qualitative in nature. Some of the uncertainties crucial to the real life application of the EMI technique have been resolved.

Numerical modeling of the PZT-structure interaction was also attempted using commercial FEM software, ANSYS version 8.1. Novel modeling and analysis incorporating the PZT patch, bonding layer and host structure was performed to simulate the PZT-structure interaction in the EMI technique application. Advantages over the existing impedance-based analytical modeling as well as FEA-based impedance modeling were discussed.

Potential application of smart system integrating the piezo-impedance transducer and FBG based strain sensor in the monitoring of structural health was studied through experimental tests on rock structures. The strengths and weaknesses of each sensor were discussed and their potential integrated application, complementing each others was proposed.

In the proceeding sections, an overall summary of the imperative development of this thesis is presented, followed by recommendations for further research works.

7.2 Research Conclusions and Contributions

(i) Consistency of admittance signatures under different environmental conditions

Major environmental factors influencing the admittance signatures are the temperature and humidity. Repeatability of admittance signatures, in terms of modal frequency and magnitudes of resonance peaks, from the PZT patch surface bonded on lab-sized aluminum structures under various environmental conditions was found to be excellent for a monitoring period of up to one and a half year; provided that the host structure remained healthy throughout that period. Highest consistency was shown by the patches placed in the laboratory (room condition). Patches put under nominal site condition also performed very well even for those left unprotected. The admittance signatures acquired from the patches buried in soil fluctuated slightly.

Resonance peaks of the admittance signatures acquired from the PZT patches embedded inside concrete showed consistent rightward shift against time. This is caused by gradual stiffening of the curing concrete. In this case, constant update of the admittance signatures as baseline is mandatory for effective SHM.

Considerable fluctuations of the admittance signatures from patches bonded on rock structure could be observed, but no trend of deterioration against time was apparent. The fluctuations were conceived to be caused by humidity variations due to the porous nature of the rock. However it does not affect the modal frequency (horizontal signature shift). Hence, application of the EMI technique remains feasible if an appropriate compensation technique is applied.

(ii) Protection of surface bonded PZT patch – During installation and servicing

An innovative protective method was developed to prevent the fragile PZT patch from breaking, especially during installation, by attaching a thin aluminum plate on the top surface of the patch using silicone rubber. This method economically overcomes the breakage problem of the PZT patch during installation and also during servicing. The very soft (low stiffness) silicone rubber also minimizes the adverse effect caused by the aluminum plate on

the actuation and sensing capability of the patch. The plate could also be removed if desired after the patch is securely bonded onto the host structure.

On the other hand, for bare PZT patch surface bonded onto host structure, those protected with silicone rubber shows higher repeatability. As expected, higher grade silicone demonstrated relatively higher consistency.

(iii) Effect of bonding thickness on admittance signatures

Various experimental case studies conducted on PZT patch sized 10mm x 10mm x 0.3mm showed that the effect of bonding can be neglected even for thickness up to $2/3$ of the surface bonded PZT patch's thickness provided that the excitation frequency does not exceed 100 kHz. Above that, the adverse effect of thick (larger than $1/3$ of patch's thickness) bonding is obvious. With thicker bonding and at high frequency of excitation, the PZT resonance will dominate the structural resonance as a result of localized actuation and sensing, rendering contamination to the admittance signatures and reduction in the damage detection capability. This observation is numerically verified. It should be noted that this observation is general, but the allowable frequency for different patches with different sizes may vary due to different PZT's resonances.

A preferable bonding thickness (typically about 0.03mm, less than $1/3$ of 0.1mm patch) can be easily attained on flat surface by squeezing out the excessive adhesive between the patch and the host structure during the process of bonding, and by applying sufficient static pressure during the process of curing. The minimum thickness of bonding film between PZT patch and flat aluminum surface achieved in this study was $27\mu\text{m}$.

Recommendation from Bhalla (2004) stating that the bonding thickness should be lesser than $1/3$ of the PZT patch is verified experimentally as well as numerically, and accompanied by more concrete observations and explanations in this study.

(iv) Repeatability of signatures from different PZT patches with similar PZT-structure iterations

Repeatability of the admittance signatures (host structural resonances) acquired from PZT patches surface bonded on symmetrical locations on a structures was very high, especially for excitation frequency below 100 kHz . With varying bonding thickness (even with bonding thickness more than one-third of the patch), the admittance signatures from patches bonded on symmetrical location still exhibited high repeatability.

With frequency exceeding 200 kHz , repeatability dropped significantly as the sensing and actuation of the PZT patch became increasingly localized and very sensitive to minor differences. Slight difference in bonding thickness or placement locations changed the admittance signatures.

Hence, if repeatability of signatures is a major concern, the excitation frequency should not exceed 100 kHz unless a very accurate placement could be assured.

(v) Effect of temperature on admittance signatures

Within the small temperature difference typically experienced in the tropical countries, the effect of temperature changes on the admittance signatures was found to be insignificant. The signature deviation caused by temperature can be viewed as a combination of linear vertical and horizontal shift.

At elevated temperature, the horizontal shift of the admittance signatures against frequency plot is mainly caused by “softening” of the host structure. The vertical shift, on the other hand, is largely caused by the adverse effect of bonding.

The temperature effect also amplifies with increasing frequency of excitation. Similar to the abovementioned reason, the adverse effect of bonding is aggravated by increase in temperature, causing the PZT resonance peak to shift to the left and dominates the admittance signatures. The admittance signatures were found to be relatively sensitive to changes in temperature. Considerable shifts were observed with a mere 5°C of temperature difference.

The temperature effect on admittance signatures can be conveniently compensated using the empirical technique proposed by Park et al. (1999). A user friendly software written in

CHAPTER 7 CONCLUSIONS AND FUTURE WORKS

Matlab 6.5 workspace based on the compensation technique was successfully implemented to compensate for the admittance signatures acquired from PZT patches bonded on host structures of different materials including aluminum, concrete and rock with a temperature variation of up to 50°C .

The technique is also applicable to patches with relatively thick bonding, but is sometimes less effective. Strength of this technique lies in the fact that the software based statistical approach could be fully automated and easily applied to various materials and structures without the need of complex modeling. With the admittance signatures compensated, the damage detection capability of the EMI technique could be retained under fluctuating temperature.

Combining the observations from both the effect of bonding as well as temperature, it can be inferred that under fluctuating temperature, a thin bonding is highly recommended to reduce contamination to the admittance signatures caused by the first PZT resonance peak. Maximum frequency adopted should not exceed 200 kHz under such circumstances and preferably not more than 100 kHz if the bonding film is thick and temperature is high.

In real-life applications, it is advisable that the admittance signatures be acquired a number of times per day at fix timing. Subsequently, the signatures acquired at different timing are to be compared with their corresponding baseline counterparts in order to minimize the effect of temperature. Also, the frequency range selected for compensation should not exceed 20 kHz due to deviating linearity at wider range. The frequency range should be further reduced to 10 kHz when temperature difference is large especially for patches with thick bonding. The tedious procedures can be largely alleviated with the use of the software.

(vi) Differentiation between damage and temperature

A novel approach to differentiate the effect of temperature from actual damage is proposed by observing the admittance at very high frequency range ($200 - 1000\text{ kHz}$). Temperature induced deviation triggers the shift of PZT's resonance peaks at higher frequency range which does not exist in the case of damage.

(vii) Differentiation between damage on structure and damage on PZT patch

Making use of the fact that higher frequency range ($> 200\text{ kHz}$) better reflects the

vibration of the PZT patch, damage inflicted on PZT patch could be distinguished from structural damage by observing the admittance signatures at very high frequency range (200 – 1000 kHz). Damage induced on PZT patch (as long as the patch is still functional) will not affect the modal frequency of the structural resonance though it may affect the structural peak's height. Therefore, it could be deduced that different frequency range can be informative in the application of the EMI technique if they were suitably utilized.

(viii) Weaknesses of non-parametric approaches as damage quantifiers

Conventional non-parametric damage detection and quantification approaches such as root mean square deviation (RMSD) and damage index (DI) was found to be ineffective in real life application of the EMI technique. The non-parametric approaches, which primarily measure the vertical difference in two signatures of different state, can be erroneous and confusing as vertical shifts can easily be triggered by various external factors, including ambient temperature, humidity, bonding thickness and frequency step selected. Horizontal shift or change in modal frequency is a much better representation as it is relatively steadfast to external disturbance and reflects the structure's vibrational modes or health more accurately.

(ix) Numerical simulation on the PZT-structure interaction of the EMI technique

Novel numerical simulation of the PZT-structure interaction incorporating the PZT patch, bonding layer and the structure in the frequency range normally employed in the EMI technique was attempted and found to be more realistic than the existing impedance based analytical modeling as well as FEA-based impedance modeling.

In the 3-D modeling of freely suspended PZT patch, the novel numerical model used was proven to be able to predict some resonance peaks unpredicted by the conventional impedance based analytical model, when compared to the experimental results. Previous explanation stating that the unpredicted modes were caused by imperfect shape during manufacturing was proven to be incorrect. Reasonable accuracy was achieved for frequency of up to 1000 kHz.

Simulation of PZT-structure interaction incorporating the bonding layer on a lab-sized

aluminum beam showed promising results as good match between the numerical and experimental results of both structural modal frequency and peaks' amplitudes was achieved for up to 100 kHz . The outcome also showed more accurate prediction over the conventional FEA-based impedance modeling. Several similar models with varying bonding thickness were simulated and were found to be inline with the experimental observations.

Through the numerical study, it was also found that for excitation frequency lower than 100 kHz , the structural modal frequency is unaffected by the bonding thickness (even when the bonding thickness is larger than $1/3$ of the patch), though the peaks' height could be faintly affected. This implies that if the peaks' amplitude were not a major concern and frequency range does not exceed 100 kHz , the effect of bonding can be negligible.

Modeling of more complex structure, in this case, an L-shaped beam was also attempted and was found to match well with the experimental results.

When compared to the FEA-based impedance model, this novel numerical modeling technique is more convenient and more accurate. This is because the actuation and sensing of the PZT patch could be simulated across the finite contact area between the patch and the host structure instead of simplification into point force or perimeter forces as adopted in the FEA-based impedance model. At lower frequency of excitation ($<1\text{ kHz}$), the loss in accuracy could be negligible as shown by previous researchers (Lalande, 1995), but the simplification was found to be intolerable at high frequency, such as those employed in the EMI technique.

(x) Integrated use of smart materials in SHM

A novel SHM technique employing both piezo-impedance transducer and FBG based strain sensor was successfully implemented on lab-sized cylindrical rock structure. It was found that the inherent characteristics of each smart material could complement their respective shortcomings and thus form a more robust SHM system. The FBG based strain sensor showed promising strain measurements which were at least as accurate as the conventional ESG. The admittance signatures acquired from piezo-transducer was also found to be well correlated to the extent of damage in the host structures. Robustness of the EMI technique in giving early warning during the presence of incipient cracks as well as impending failure was proven when applied on the rock structure.

With the two sensors applied collectively, a more robust SHM system capable of monitoring strain-induced damage (by FBG sensor) such as compressive, tensile or bending failure, as well as non-strain-induced local damages (by piezo-impedance transducer) such as cracking and loosening of bolts was proposed.

In real-life application, FBG sensors are advised to be placed at highly strained location to capture the potential strain-induced damage whereas the PZT patch should be located at places near joints, connections and cracking prone locations.

7.3 Recommendations for Future Works

(i) Consistency of admittance signatures from EMI technique

With consistency of admittance signatures acquired from the PZT patches under nominal conditions assured, further investigations on harsher environmental conditions such as those exposed to electromagnetic interference, chemical attack, vibration, cyclic heating and cooling, cyclic loading, humidity fluctuation, frost and thaw, dirt etc should be attempted.

In addition, a real time automatic updating system for the compensation of the effect of curing in concrete is essential if the EMI technique is applied on concrete structures. A compensation technique for the effect of humidity in porous materials such as rocks should also be developed.

(ii) Long term protection of PZT patch

The existing economical method of using silicone rubber as protection may not be sufficiently robust to prevent human interference. Thus, a more robust long term protection of the PZT patch is desired.

(iii) Effect of bonding and temperature

Adhesive with higher stiffness and more stable to temperature changes should be developed to ensure a more effective strain transfer. Such adhesive will minimize the adverse effect on admittance signatures caused by the PZT resonance's peak.

More study should also be conducted to investigate the potential use of the very high

frequency range ($> 200 \text{ kHz}$) in which the PZT resonance dominates in the EMI technique.

A systematic and automatic temperature and humidity compensation algorithm ought to be developed. Suitable signatures acquisition period should also be established to minimize the effect of temperature and humidity.

More experimental, analytical or numerical studies are necessary to establish more exact guidelines stating the general frequency range suitable to be used in the EMI technique for PZT patches with different sizes, bonding thickness and at different temperature for host structures of different materials.

The temperature compensation technique adopted in this study assumed that the temperature induced horizontal shift in admittance signatures is uniform, which is approximately true within narrow frequency band. It is necessary to further investigate the effect of varying horizontal shift against frequency at different temperature as well as to develop a more comprehensive compensation technique capable of compensating a wider range of frequency.

A quality control technique, capable of controlling the thickness of the bonding layer ought to be developed, especially for uneven surface or curved surface, to minimize the adverse effect of bonding.

(iv) Damage detection and characterization

Being qualitative in nature, the EMI technique depends solely on the admittance signatures for damage detection and characterization. It is therefore essential to develop a more systematic damage calibration chart based on experimental, numerical and theoretical studies for identification of the various types of damages on host structures of different materials. Also, the development of damage detection and characterization approach in the future should focus on the horizontal shifts of the admittance signatures, which is a better representation of structural changes.

(v) Other practical issues related to applications of EMI technique

Future studies should concentrate on investigating the placement of PZT patches in complex, large host structures if an efficient SHM system is to be achieved. Optimal number

of patches placed at appropriate locations will maximize the effectiveness and minimize the cost.

Current application of the EMI technique requires commercialized impedance analyzer to provide the necessary voltages to the PZT patch as well as to measure the modulated current. They possess various shortcomings such as limited allowable length of wires (<5m), very bulky and expensive, which prevent its effectiveness in real life monitoring, especially of large scale civil structures. Future research should target on customizing some cost effective impedance analyzer suitable for the EMI technique.

Another potential problem arises would be the large number of wires required for monitoring large scale civil structures as each PZT patch requires a pair of wires. Multiplexing of the patches is now at its embryonic stage with more in depth study necessary.

(vi) FE modeling of EMI technique

With the novel FE modeling of PZT-structure interaction at high frequency of excitation been successfully implemented in this study, a series of numerical study employing the modeling technique could be conducted in the future to better understand the PZT-structure interaction under different circumstances. Numerical study incorporating the bonding thickness under different circumstances can be attempted. Study could be focused on investigating different bonding conditions such as imperfect bonding, slanted PZT patch, bonding on curved surface, strain transfer at high strain rate, shear lag effect etc. Study on temperature effect or compensation would also be possible with the use of FE software incorporated with this feature.

Another major issue in the modeling of PZT-structure interaction at high frequency of excitation is accurate simulation of the boundary condition. In real-life structure, the actual boundary condition is generally different and more complicated than the ideal case. Guidelines for simulating real-life boundary condition capable of providing sufficiently close approximation ought to be established.

FE model built in this study focused on the usage of hexahedral element, which generally provides more accurate results. However, joining of nodes between different surfaces (such as curved surfaces) could sometimes be very difficult. Thus, simulation using other shapes of

elements such as the tetrahedral shape, which are more powerful in simulating curved surfaces should be attempted to check for its accuracy.

This 3-D numerical model enables the simulation of the PZT patch's actuation in the thickness direction. This inherently allows the simulation of embedded PZT patch, which is unattainable in conventional impedance based analytical model or FEA-based impedance model. This opens a path for the study of interaction between embedded PZT patch and structure.

More accurate prediction of the beta value adopted as a parameter in damping is essential for a more accurate simulation. Standard chart tabulating the possible ranges of beta values for different materials should be setup for the ease of modeling.

On the other hand, accuracy of the static based parameters especially when used in the modeling of high frequency dynamic excitation requires more careful investigation. If necessary, suitable modification factor has to be incorporated.

Future studies could also focus on the modeling of large scale structures with varying element sizes. The path for investigating the sensing range of the EMI technique using the numerical simulation is also opened.

This novel numerical modeling technique opens up a path to the study of bonding effect such as shear lag in the application of the EMI technique. With the advanced FE software, further investigations incorporating the effect of temperature, complex structures with varying boundary conditions, and loadings could also be conducted.

(vii) Integrated use of smart materials in SHM

Integrated use of different smart materials to form a more realistic smart structure capable of self monitoring and healing remains as a major challenge for SHM researchers. Besides piezoelectric materials and optical fibers, smart materials such as shape memory alloy could be incorporated for repair (Peairs, 2004b).

Sensible utilizations of both piezo-impedance transducer and FBG based strain sensor to obtain maximum information about the health of the host structure could be a major direction of study in this area. The strengths and weaknesses of both smart materials in SHM need to be better understood to determine the optimum placement locations.

CHAPTER 7 CONCLUSIONS AND FUTURE WORKS

Practicality of SHM using more than one smart material, especially from the economical point of view should be carefully scrutinized before real life application is possible.

REFERENCES

REFERENCES

Abe, M., Park, G. and Inman, D. J. (2002), "Impedance-Based Monitoring of Stress in Thin Structural Members", Proceeding of 11th International Conference on Adaptive Structures and Technologies, October 23-26, Nagoya, Japan, pp. 285-292.

Agilent Technologies (2003), Test and Measurement Catalogue, USA.

Aktan, A. E., Helmicki, A. J. and Hunt, V. J. (1998), "Issues in Health Monitoring for Intelligent Infrastructure", Smart Materials and Structures, Vol. 7, No. 5, pp. 674-692.

Alfredo, R. D. F. (2003), "The Impact of Finite-Stiffness Bonding on the Sensing Effectiveness of Piezoelectric Patches", Smart Materials and Structures, Vol. 12, N5 – N8.

Andre, J. C. (1996), "Smart Materials and Sensor: A Reality or Dream of Tomorrow?" Proceedings of the Third international conference on intelligent materials, June 3-5, Lyon, France, pp 240 – 254.

Annamdas, V. G. M. (2004), "Improved Method of Structural Health Monitoring Using Smart Materials", first year report for PhD thesis, Nanyang Technological University, Singapore.

ANSYS Reference manual; Release 8.1 (2004), ANSYS Inc., Canonsburg, PA, USA.

Ayres, J. W., Lalande, F., Chaudhry, Z. and Rogers, C. A. (1998), "Qualitative Impedance-Based Health Monitoring of Civil Infrastructures", Smart Materials and Structures, Vol. 7, No. 5, pp. 599-605.

REFERENCES

Banan, M. R. and Hjelmstad, K. D. (1994), "Parameter Estimation of Structures from Static Response. I. Computational Aspects", Journal of Structural Engineering, ASCE, Vol. 120, No. 11, pp. 3243- 3258.

Baran, M. (1996), "The Optical Fiber for Temperature Measurement", Proceedings of the Third international conference on intelligent materials, June 3-5, Lyon, France, pp. 2 – 15.

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

Bhalla, S. (2004) "A Mechanical Impedance Approach for Structural Identification, Health Monitoring and Non-Destructive Evaluation Using Piezo-Impedance Transducer", PhD Thesis, Nanyang Technological University, Singapore.

Bhalla, S. and Soh, C. K. (2003), "Structural Impedance Based Damage Diagnosis by Piezo-Transducers", Earthquake Engineering and Structural Dynamics, Vol. 32, pp. 1897 -1916.

Bhalla, S. and Soh, C. K. (2004a), "Structural Health Monitoring by Piezo-impedance transducers. I: Modeling", J. of aerospace engineering, Vol. 17, pp.154 -165.

Bhalla, S. and Soh, C. K. (2004b), "Structural Health Monitoring by Piezo-impedance transducers. II: Applications", J. of aerospace engineering, Vol. 17, pp.166 - 175.

Boller, C. (2001), "Ways and Options for Aircraft Structural Health Management", Smart Materials and Structures, Vol. 10, pp. 432-440.

REFERENCES

Chaudry, Z., Joseph, T., Sun, F., and Rogers, C. A. (1995), "Local-area Health Monitoring of Aircraft Via Piezoelectric Actuator/Sensor Patches," Proceedings of AIAA/ASME/ASCE/AHS/ASC 36th structures, structural dynamics and materials conference, adaptive structures forum, New Orleans, LA, pp. 2243-2248.

Chaudhry, Z., Sun, F. P., and Rogers, C. A. (1994), "Health Monitoring of Space Structures Using Impedance Measurements", Fifth International Conference on Adaptive Structures, Sendai, Japan, Dec. 5 – 7, pp. 584 – 591.

Cheng, C. C and Wang, P. W. (2001), "Applications of the Impedance Method on Multiple Piezoelectric Actuators Driven Structures", Journal of Vibration and Acoustics, Transactions of ASME, Vol. 23, Apr., pp. 262 – 268.

Chong, K. P., Carino, N. J., and Washer G. (2003), "Health Monitoring of Civil Infrastructures", Smart Materials and Structures, Vol. 12, pp. 483-493.

Crawley, E. F., de Luis, J. (1987), "Use of Piezoelectric Actuators as Elements of Intelligent Structures", AIAA Journal, Vol. 25, No. 10, pp. 1373-1385.

Dewynter-Marty, V., Ferdinand, P., Bocherens, E., Carbone, R., Beranger, H., Bourasseau, S., Dupont, M., and Balageas, D. (1998), "Embedded Fiber Bragg Grating Sensors for Industrial Composite Cure Monitoring", Journal of Intelligent Material Systems and Structures, Vol. 9, pp. 785-799.

Dow Corning Corporation (2006), <http://www.dowcorning.com>.

Esteban, J. (1996), "Analysis of the sensing region of a pzt actuator/sensor", PhD Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

REFERENCES

Fairweather, J. A. (1998), "Designing with Active Materials: An Impedance Based Approach", PhD Thesis, Rensselaer Polytechnic Institute, New York.

Gandhi, M. V. and Thompson, B. S. (1992), "Smart Materials and Structures", Chapman and Hall, London.

Gere, J. M. (2001), "Mechanics of Materials", 5th edition, Brooks/Cole, US.

Giurgiutiu, V. and Rogers, C. A. (1998), "Recent Advancements in the Electro-Mechanical (E/M) Impedance Method for Structural Health Monitoring and NDE", Proceedings of Smart Structures and Materials Conference, San Diego, California, March, SPIE Vol. 3329, pp. 536-547.

Giurgiutiu, V. and Zagari, A. N. (2000), "Characterization of Piezoelectric Wafer Active Sensors", Journal of Intelligent Material Systems and Structures, Vol. 11, pp. 959-976.

Giurgiutiu, V., Zagari, A. N. and Bao, J. (2004), "Damage Identification in Aging Aircraft Structures with Piezoelectric Wafer Active Sensors", Journal of Intelligent Material Systems and Structures, Vol. 15, pp. 673-687.

Ha, S. K., Keilers, C., and Chang, F. K. (1992), "Finite Element Analysis of Composite Structures Containing Distributed Piezoceramic Sensors and Actuators", AIAA Journal, Vol. 30, No. 3, pp. 772-780.

Hewlett Packard (1996), HP LF 4192A Impedance Analyzer, Operation Manual, Japan.

Hi-Bond (2006), www.hi-bond.co.uk

REFERENCES

IEEE (1987), IEEE Standard on Piezoelectricity, Std. 176, IEEE/ANSI.

Ihn, J. and Chang, F. K. (2004a), "Detection and Monitoring of Hidden Fatigue Crack Growth Using A Built-In Piezoelectric Sensor/Actuator Network: I. Diagnosis", Smart Materials and Structures, Vol. 13, pp. 609-620.

Ihn, J. and Chang, F. K. (2004b), "Detection and Monitoring of Hidden Fatigue Crack Growth Using a Built-In Piezoelectric Sensor/Actuator Network: II. Validation Using Riveted Joints and Repair Patches", Smart Materials and Structures, Vol. 13, pp. 621-630.

Kabeya, K. (1998), "Structural Health Monitoring Using Multiple Piezoelectric Sensors and Actuators", Master Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Krishnamurthy, K., Lalande, F. and Rogers, C. A. (1996), "Temperature Effects on Piezoelectric Elements Used as Collocated Actuator/Sensors", Proceedings of SPIE North American Conference on Smart Structures and Materials, Vol. 2717, pp. 302 - 310

Kumar, S. (1991), "Smart Materials for Acoustic or Vibration Control", Ph.D. Dissertation, Pennsylvania State University, PA.

Lalande, F. (1995), "Modelling of the Induced Strain Actuation of Shell Structures", PhD Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, V.A., pp. 152

Lee, I. and Han, J.-H. (1996), "Optimal Placement of Piezoelectric Actuators in Intelligent Structures Using Genetic Algorithm", Proceedings of the Third international conference on intelligent materials, June 3-5 , Lyon, France, pp 872 - 882

REFERENCES

Liang, C., Sun, F. P. and Rogers, C. A. (1993), "An Impedance Method for Dynamic Analysis of Active Material Systems", Proceedings of AIAA/ ASME/ ASCE/ Material systems, La-Jolla, California, pp. 3587-99.

Liang, C., Sun, F. P. and Rogers, C. A. (1994), "Coupled Electro-Mechanical Analysis of Adaptive Material Systems- Determination of Actuator Power Consumption and System Energy Transfer", Journal of Intelligent Material Systems and Structures, Vol. 5, pp. 12-20.

Lim, Y. Y. (2004), "Structural Identification by Smart Materials", Final year report, Nanyang Technological University, Singapore.

Lim, Y. Y., Bhalla, S. and Soh, C. K. (2006), "Structural Identification and Damage Diagnosis Using Self-Sensing Piezo-Impedance Transducers", Smart Materials and Structures, Vol. 15, pp. 987-995.

Lin, Y. B., Chang, K. C., Chern, J. C. and Wang, L. A. (2004), "The Health Monitoring of a Prestressed Concrete Beam by Using Fiber Bragg Grating Sensors", Smart Materials and Structures, Vol. 13, pp. 712-718.

Littlefield, A. G. (2000), "Application of the Impedance Method of Modeling Active Materials to Plate Structures", Doctoral Thesis, Rensselaer Polytechnic Institute, pp. 154.

Liu, S. C., Chong, K. P. and Singh, M. P. (1994), "Civil Infrastructure Systems Research: Hazard Mitigation and Intelligent Material Systems", Smart Materials and Structures, Vol. 3, pp. A196 – A174.

REFERENCES

Makkonen, T., Holappa, A., Ella, J. and Salomaa, M. M. (2001), "Finite Element Simulations of Thin-Film Composite BAW Resonators", IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 48, No. 5, pp. 1241-1258.

Michel, L., Labarrere, M., Gafsi, R., Malki, A. and Lecoy, P. (1996), "Impact Detection and Vibration Sensing for Material Composite Structures by Integrated Optic Fibre Sensors", Proceedings of the Third international conference on intelligent materials, June 3-5 , Lyon, France, pp 230 – 234.

Mide (2006), <http://www.mide.com/>

Moveni, S. (2003), "Finite Element Analysis, Theory and Application with ANSYS", 2nd edition, Pearson Education, Inc, New Jersey, USA.

Naidu, A. S. K. and Bhalla, S. (2002), "Damage Detection in Concrete Structures with Smart Piezoceramic Transducers", Proceedings of ISSS-SPIE International Conference on Smart Materials, Structures and Systems, edited by B. Dattaguru, S. Gopalakrishnan, S. Mohan, 12-14 December, Bangalore, Microart Multimedia Solutions (Bangalore), pp. 639-645.

Naidu, A.S.K. and Soh, C. K. (2004), "Identifying Damage Location with Admittance Signatures of Smart Piezo-Transducers", Journal of Intelligent Material Systems and Structures, Vol. 15, pp. 627-642.

National Environment Agency Singapore, (2006) official website:

<http://app.nea.gov.sg/cms/htdocs/article.asp?pid=1088>

REFERENCES

- Nguyen, C., Pietrzko, S. and Buetikofer, R. (2004), "The Influence of Temperature and Bonding Thickness on The Actuation of a Cantilever Beam by PZT Patches", Smart Materials and Structures, Vol 13, pp. 851-860.
- Ong, C. W. (2003) "Dynamic Identification and Health Monitoring of Structural Systems with the Electromechanical Impedance Method", Master Thesis, Nanyang Technological University, Singapore.
- Ong, C.W., Yang, Y., Wong, Y.T., Bhalla, S., Lu, Y., Soh, C.K., (2002) "The effects of adhesive on the electro-mechanical response of a piezoceramic transducer coupled smart system", International Conference on Smart Materials, Structures and Systems, Proceedings of ISSS-SPIE 2002, Edited by B. Dattaguru, S. Gopalakrishnan, S. Mohan, Dec 12 – 14, Bangalore, pp. 191 – 197.
- Palm, W. J. (2001), "Introduction to Matlab 6 for Engineers", McGraw-Hill, New York.
- Pan, J., Hansen, C. H. and Snyder S. D. (1991), "A Study of the Response of a Simply Supported Beam to Excitation by a Piezoelectric Actuator", Recent Advances in Active Control of Sound and Vibration, edited by Fuller C.R., Rogers C.A., Virginia Polytechnic Institute, pp. 39 – 49.
- Pandey, A. K. and Biswas, M. (1994), "Damage Detection in Structures Using Changes in Flexibility", Journal of Sound and Vibration, Vol. 169, No. 1, pp. 3-17.
- Park, G. (2000), "Assessing Structural Integrity Using Mechatronic Impedance Transducers with Applications in Extreme Environments", Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

REFERENCES

Park, G., Cudney, H. H. and Inman, D. J. (2000), "Impedance-Based Health Monitoring of Civil Structural Components", Journal of Infrastructure Systems, ASCE, Vol. 6, No. 4, pp. 153-160.

Park, G., Kabeya, K., Cudney, H. H. and Inman, D. J. (1999), "Impedance-Based Structural Health Monitoring for Temperature Varying Applications", JSME International Journal, Vol. 42, No. 2, pp. 249-258.

Park, S., Yun, C-B, Roh, Y. and Lee, J-J (2005), "Health Monitoring of Steel Structures Using Impedance of Thickness Modes at PZT Patches", Smart Struct. Syst., Vol. 1, pp. 339-53.

Peairs, D. M., Park, G. and Inman, D. J. (2004a), "Improving Accessibility of the Impedance-Based Structural Health Monitoring Method", Journal of Intelligent Material Systems and Structures, Vol. 15, pp. 129-139.

Peairs, D. M., Park, G. and Inman, D. J., (2004b), "Practical Issues of Activating Self-Repairing Bolted Joints", Smart Materials and Structures, Vol 13, pp. 1414 – 1423.

PI Ceramic (2006), Product Information Catalogue, Lindenstrabe, Germany, <http://www.piceramic.de>.

Rao, Y. J., Ribeiro, A. B. L., Jackson, D. A., Zhang, L. and Bennion, I. (1995), "Combined Spatial- and Time-Division-Multiplexing Scheme for Fibre Grating Sensors with Drift-Compensated Phase-Sensitive Detection", Opt. Lett., Vol. 20, pp. 2149-51.

Rao, Y. J. (1997), "In-fibre Bragg Grating Sensors", Meas. Sci. Technol., Vol. 8, pp. 355-375.

REFERENCES

Rao, Y. J. (1999), "Recent Progress in Applications of In-Fibre Bragg Grating Sensors", Optics and Lasers in Engineering, Vol. 31, pp. 297-324.

Rogers, C. A., Barker, D. K., and Jaeger, C. A. (1988), "Introduction to Smart Materials and Structures", Smart Materials, Structures and Mathematical Issues, U.S., Army Research Office Workshop, Virginia Polytechnic Institute and State University, Sept. 15 – 16, pp. 17 – 27.

RS Components (2006), Northants, UK, <http://www.rs-components.com>.

Sanayei, M. and Saletnik, M. J. (1996), "Parameter Estimation of Structures from Static Strain Measurements. I: Formulation", Journal of Structural Engineering, ASCE, Vol. 122, No. 5, pp. 555-562.

Schulz, M. J., Sundaresan, M. J., McMichael, J., Clayton, D., Sadler, R. and Nagel, B. (2003), "Piezoelectric Materials at Elevated Temperature", Journal of Intelligent Material Systems and Structures, Vol. 14, pp. 693-704.

Schwartz, M. (2005), "Encyclopedia of Smart Materials", John Wiley & Sons.

Sirohi, J. and Chopra, I. (2000a), "Fundamental Behaviour of Piezoceramic Sheet Actuators", Journal of Intelligent Material Systems and Structures, Vol. 11, No. 1, pp. 47-61.

Sirohi, J. and Chopra, I. (2000b), "Fundamental Understanding of Piezoelectric Strain Sensors", Journal of Intelligent Material Systems and Structures, Vol. 11, No. 4, pp. 246-257.

REFERENCES

Soh, C. K., Tseng, K. K. H., Bhalla, S. and Gupta, A. (2000), "Performance of Smart Piezoceramic Patches in Health Monitoring of a RC Bridge", Smart Materials and Structures, Vol. 9, No. 4, pp. 533-542.

Srinivasan, A. V. and Michael McRarland, D. (2001), "Smart Structures, Analysis and Design", 1st edn, Cambridge: Cambridge University Press, pp. 1-23.

Storoy, H., Saether, J. and Johannessen, K. (1997), "Fiber Optic Monitoring During a Full Scale Destructive Bridge Test", Journal of Intelligent Material Systems and Structures, Vol. 8, pp. 633-643.

Sun, F. P., Chaudhry, Z., Rogers, C. A., Majmundar, M. and Liang, C. (1995) "Automated Real-Time Structure Health Monitoring via Signature Pattern Recognition", edited by I. Chopra, Proceedings of SPIE Conference on Smart Structures and Materials, San Diego, California, Feb.27-Mar1, SPIE vol. 2443, pp. 236-247.

Takagi, T. (1996), "The Concept and Recent Research on Intelligent Materials", Proceedings of the Third international conference on intelligent materials, June 3-5 , Lyon, France, pp. 2 – 15.

Tjin, S. C., Rupali, S., Moyo P., Brownjohn, J. M. W. and Ngo, N. Q. (2002), "Application of Fibre Bragg Grating Based Sensors for Civil Infrastructure Health Monitoring." Proceedings, ISSS-SPIE International Conference on Smart Materials, Structures and Systems, Bangalore, 12-14 December, pp. 683-690.

Tseng, K. K. H., Tinker M. L., Lassiter J.O. and Peairs D.M. (2003), "Temperature dependency of impedance-based nondestructive testing", Experimental Techniques, pp. 33-36.

REFERENCES

Winston, H. A., Sun, F. and Annigeri, B. S. (2001), "Structural Health Monitoring with Piezoelectric Active Sensors", Journal of Engineering for Gas Turbines and Power, ASME, Vol. 123, No. 2, pp. 353-358.

Xu, J. F., Yang, Y. W., and Soh, C. K. (2004), "E/M Impedance-Based Structural Health Monitoring with Evolutionary Programming", Journal of Aerospace Engineering, ASCE.

Xu, Y. G. and Liu, G. R. (2003), "A Modified Electro-mechanical Impedance Model of Piezoelectric Actuator-Sensors for Debonding Detection of Composite Patches", Journal of Intelligent Material Systems and Structures, Vol. 13, No. 6, pp. 389-396.

Yang, Y., Bhalla, S., Wang, C., Zhao, J. and Soh, C. K. (2005), "Advanced Monitoring Techniques Applied to Underground Structures", UTRE technical report no.6, DSTA-NTU Underground Technology and Rock Engineering (UTRE) Program.

Zagrai, A. N. and Giurgiutiu, V. (2001), "Electro-Mechanical Impedance Method for Crack Detection in Thin Plates", Journal of Intelligent Material Systems and Structures, Vol. 12, No. 12, pp. 709-718.

Zhou, S., Liang, C. and Rogers, C. A. (1995), "Integration and Design of Piezoceramic Elements in Intelligent Structures", Journal of Intelligent Material Systems and Structures, Vol. 6, No. 6, pp. 733-743.

Zhou, S., Liang, C. and Rogers C. A. (1996), "An Impedance-Based System Modeling Approach for Induced Strain Actuator-Driven Structures", Journal of Vibrations and Acoustics, ASME, Vol. 118, No. 3, pp. 323-331.

REFERENCES

Zimmerman, D. C. and Kaouk, M. (1994), "Structural Damage Detection Using a Minimum Rank Update Theory", Journal of Vibration and Accoustics, Vol. 116, pp. 222-231.

AUTHOR'S PUBLICATION

Lim, Y. Y., Bhalla, S. and Soh, C. K. (2006), "Structural Identification and Damage Diagnosis Using Self-Sensing Piezo-Impedance Transducers", Smart Materials and Structures, Vol. 15, pp. 987-995.

APPENDIX A

Conductance Signatures against Frequency Plot for Specimen B1 (10 – 100 kHz)

APPENDIX B

Temperature Compensation Algorithm Written in Matlab 6.5

```
% Empirical temperature compensation algorithm for conductance signatures
(Park et al., 1999)
% Design for user specified input frequency between 10-100 kHz
% To obtain the vertical and horizontal compensation factor: delta v and
delta h
% This program works for a frequency step of 0.1kHz

clear;
temperature1 = dlmread('Beam_b2_30.txt','\t');           % Baseline
temperature
temperature2 = dlmread('Beam_b2_50.txt','\t');           % Elevated
temperature

%temperature(1,1)   = 10 kHz
%temperature(11,1)  = 11 kHz
%temperature(901,1) = 100 kHz
%temperature(301:601,1) = 40 - 70 kHz

%Prompt user to input starting and ending frequency:
startf = input('\n\n Start frequency (kHz) = ');
endf   = input(' End frequency   (kHz) = ');

%Change the respective frequency and conductance signatures to matrix
convenient for calculation
f = temperature1( (10 * (startf - 10) + 1) : (10 * (endf - 10) + 1) ,1);
G1 = temperature1( (10 * (startf - 10) + 1) : (10 * (endf - 10) + 1) ,2);
    %Conductance
G2 = temperature2( (10 * (startf - 10) + 1) : (10 * (endf - 10) + 1) ,2);

n = size(G1);                               %No of data points
n = n(1,1);

%Specify the number of points (trial and error) required, each move = 0.1
kHz

move = input(' Points to move (each point = 0.1 kHz) = ');
max1 = G1(n-move);
max2 = G2(n-move);
```

```
%Allow 'move' number of points to search for a average maximum value (in
the higher f range of interest) excluding peaks
for I = (n-move):n,
if G1(I) < max1
    max1 = G1(I);
end
if G2(I) < max2
    max2 = G2(I);
end
end
```

```
% Evaluate delta v
```

```
sumG1 = 0;
```

```
sumG2 = 0;
```

```
total = 0;
```

```
% The loop is to ensure that the values for obtaining delta v exclude peaks
(as peaks height may vary with temperature)
```

```
% deltav is the average vertical difference between higher temp and lower
temp
```

```
% Assume base of higher temp always > lower temp, which is true most of
the time
```

```
for I = move:(n - move),
    if (G1(I) < max1) & (G2(I) < max2)
        sumG1 = sumG1 + G1(I);
        sumG2 = sumG2 + G2(I);
        total = total + 1;
    end
end
```

```
deltav = (sumG2 - sumG1)/total;
```

```
% Evaluate delta h
```

```
M = 0;
```

```
h = 0;
```

```
K = 1;
```

```
smallest_M = 1;
```

```
%(I - h) is equivalent to shifting higher temp values to the right by h
%For loop to search for minimum Damage Index by shifting peaks to right
(step = 0.1 kHz)
```

```
for h = 0:(move-1),
    for I = move:(n - move),
```



```

        M = M + (G1(I) - (G2(I-h)-deltav))^2;
    end

    if M < smallest_M
        smallest_M = M;
        smallest_dh = h/10;           %Divide by 10 to change back to 0.1
kHz
    end

%Damage Index for each frequency
    DI(K,1) = M;
    deltah(K,1) = h/10;
    K = K+1;
    M = 0;
end

%Output
fprintf('\n No. of points used (delta v evaluation): \n');
fprintf(' Total points          = %d\n', (endf - startf)*10 + 1);
fprintf(' Points used (both files) = %d\n', total);
fprintf(' The average verticle shift, delta v = %0.3e G\n', deltav);
fprintf(' The optimum horizontal shift, delta h = %3.1f kHz \n\n\n',
smallest_dh);
fprintf(' Damage index: \n');
fprintf(' Before compensation = %.3e\n', DI(1,1));
fprintf(' After compensation = %.3e\n', smallest_M);
fprintf('Percentage of DI after to before = %.2f\n', smallest_M /
DI(1,1)*100);

%Write Delta h and corresponding Damage Index to excel file
Output1(:,1) = deltah;
Output1(:,2) = DI;
dlmwrite('deltah & DI.xls',Output1,'\t');

%Write baseline, elevated and compensated signatures to a single excel
file
f1 = f;
f2 = f + smallest_dh;

DELTAV(1:n,1) = deltav;
g2 = G2 - DELTAV;

% Base temp
Output2(:,1) = f1(move:(n-move));

```

```
Output2(:,2) = G1(move:(n-move));

% High temp
Output2(:,4) = f1(move:(n-move));
Output2(:,5) = G2(move:(n-move));

%Compensated
Output2(:,7) = f1(move:(n-move));
Output2(:,8) = g2(move-smallest_dh*10:(n-move-smallest_dh*10));

dlmwrite('Temperature results.xls',Output2,'\t');

%Plot curve using Matlab
subplot(1,2,1);
plot(f1,G1,f1,G2);
title('Before compensation');
xlabel('f (kHz)');
ylabel('G');

subplot(1,2,2);
plot(f1,G1,f2,g2);
title('After compensation');
xlabel('f (kHz)');
ylabel('G');
```

APPENDIX C

Calculation of Maximum Allowable Element Size and Maximum Allowable Frequency Range for FE Analysis

2-D Wave number formula

$$\kappa = 1/\lambda = 2\pi f \sqrt{\frac{\rho(1-\nu^2)}{Y_{11}^E(1+\eta j)}}$$

Free-ended PZT patch

Case 1: Maximum element size 1

$f = 1000 \text{ kHz}$

Density = 7800

Young's modulus = 66.67×10^9

$\eta \approx 0.002$

Taking only the magnitude (ignoring the imaginary part, which is very small)

$$\lambda \approx 0.48 \text{ mm}$$

$$\text{Maximum element size} = 0.08 \sim 0.12 \text{ mm}$$

Case 2: Maximum element size 2

$$f = 200 \text{ kHz}$$

$$\lambda \approx 2.4 \text{ mm}$$

$$\text{Maximum element size} = 0.4 \sim 0.6 \text{ mm}$$

Case 3: Maximum frequency with element sized 0.2mm

$$\lambda_{\min} = 0.8 \text{ mm}$$

$$f_{\max} = 610 \text{ kHz}$$

Aluminum beam

$$f = 200 \text{ kHz}$$

$$\text{Density} = 2715$$

$$\text{Young's modulus} = 68.95 \times 10^9$$

$$\eta \approx 0.00067$$

$$\lambda \approx 4.2 \text{ mm}$$

$$\text{Maximum element size} = 0.7 \sim 1.1 \text{ mm}$$

APPENDIX D

**Algorithm for Calculation of Electrical Admittance Signatures of Freely
Suspended PZT patch based on 1-D and 2-D Electromechanical Coupling
Equations Written in Matlab 6.5 Workspace**

```
% This program calculates the analytical value of electrical admittance
% Obtained from free PZT through 1-D impedance-based electromechanical
coupling equation (Liang et al. 1994)
```

```
%In this case  $Z = 0$ 
```

```
M = dlmread('changing frequency_s.txt','\t');
L = 0.005; H = 0.0003; RHO = 7800; D31 = -0.00000000021;
```

```
%In this case, L is half length but w is full width
Y11E= 66700000000; E33T=0.00000002124; ETA= 0.035; DELTA= 0.015;
B = D31*D31*Y11E;
```

```
f = M(:,1); %frequency in Hz
N = size(f);
```

```
for I = 1:N,
    OMEGA(I) = 2*pi*f(I);
    A(I) = 2*OMEGA(I)*2*L*H;

    %Calculation of wave number
    cons = (RHO / (Y11E * (1 + ETA * ETA)))^0.5;
    rl(I) = L * cons * OMEGA(I);
    im(I) = L * cons * OMEGA(I) * (-0.5 * ETA);

    a(I) = (exp(-im(I)) + exp(im(I))) * sin(rl(I));
    b(I) = (exp(-im(I)) - exp(im(I))) * cos(rl(I));
    c(I) = (exp(-im(I)) + exp(im(I))) * cos(rl(I));
    d(I) = (exp(-im(I)) - exp(im(I))) * sin(rl(I));
    u(I) = c(I) * rl(I) - d(I) * im(I);
    v(I) = d(I) * rl(I) + c(I) * im(I);
    h(I) = u(I)^2 + v(I)^2;

    r(I) = (a(I) * u(I) - b(I) * v(I)) / h(I);
    t(I) = (-1.0) * (a(I) * v(I) + b(I) * u(I)) / h(I);

    G1(I) = -A(I) * (B * (t(I) + ETA*(-1 + r(I))) - DELTA * E33T);
    B1(I) = A(I) * (E33T + B * (-1 + r(I) - ETA * t(I)));
```

```
End
```

```
Y(:,1) = f/1000;
Y(:,2) = transpose(G1);
Y(:,3) = transpose(B1);
```

```
subplot(2,1,1);
plot(f/1000,G1');
subplot(2,1,2);
plot(f/1000,B1');
```

```
dlmwrite('Y for free PZT_Liang.xls',Y,'\t');
```


% This program calculates the analytical value of electrical admittance
 % Obtained from free PZT through 2-D impedance-based electromechanical
 coupling equation (Zhou et al. 1995)

%In this case $Z = 0$

M = dlmread('changing frequency.txt','\t');
 L = 0.005; H = 0.0003; RHO = 7800; D31 = -0.00000000021;

%In this case, l and w are half length and half width
 Y11E= 66700000000; E33T=0.00000002124; ETA= 0.035; DELTA= 0.015; mu =
 0.3; D = D31*D31*Y11E/(1-mu);

f = M(:,1); %frequency in Hz
 N = size(f);

```
for I = 1:N,
    OMEGA(I) = 2*pi*f(I);
    C(I) = OMEGA(I)*L*L/H;

    %Calculation of wave number
    cons = ( (RHO * (1 - mu^2)) / (Y11E * (1 + ETA * ETA)) )^0.5;
    rl(I) = L * cons * OMEGA(I);
    im(I) = L * cons * OMEGA(I) * (-0.5 * ETA);

    a(I) = (exp(-im(I)) + exp(im(I))) * sin(rl(I));
    b(I) = (exp(-im(I)) - exp(im(I))) * cos(rl(I));
    c(I) = (exp(-im(I)) + exp(im(I))) * cos(rl(I));
    d(I) = (exp(-im(I)) - exp(im(I))) * sin(rl(I));
    u(I) = c(I) * rl(I) - d(I) * im(I);
    v(I) = d(I) * rl(I) + c(I) * im(I);
    h(I) = u(I)^2 + v(I)^2;

    r(I) = (a(I) * u(I) - b(I) * v(I)) / h(I);
    t(I) = (-1.0) * (a(I) * v(I) + b(I) * u(I)) / h(I);
    E(I) = E33T + D * (-2 + 2*r(I) - ETA * (2 * t(I)));
    F(I) = -E33T * DELTA + D * (-2 * ETA + 2 * t(I) + ETA * 2 * r(I));

    G(I) = 4 * (-C(I) * F(I));
    B(I) = 4 * (C(I) * E(I));
End
```

Y(:,1) = f/1000;
 Y(:,2) = transpose(G);
 Y(:,3) = transpose(B);

subplot(2,1,1);
 plot(f/1000,G');
 subplot(2,1,2);
 plot(f/1000,B');

dlmwrite('Y for free PZT_Zhou.xls',Y,'\t');

% This program calculate the analytical value of electrical admittance
 % Obtained from free PZT through 2-D effective impedance-based
 electromechanical coupling equation (Bhalla et al. 2004)

%In this case $Z = 0$ and the Z_a term vanish as well

```
X = dlmread('changing frequency.txt','\t');
L = 0.005; H = 0.0003; RHO = 7800; D31 = -0.00000000021;
```

```
%In this case, l and w are half length and half width
Y11E= 66700000000; E33T=0.00000002124; ETA= 0.035; DELTA= 0.015; mu =
0.3;
```

```
N = 2*D31*D31*Y11E/(1-mu);
f = X(:,1); %frequency in Hz
U = size(f);
```

```
for I = 1:U,
    OMEGA(I) = 2*pi*f(I);
    M(I) = 4*OMEGA(I)*L*L/H;

    %Calculation of wave number
    cons = ( (RHO * (1 - mu^2)) / (Y11E * (1 + ETA * ETA)) )^0.5;
    rl(I) = L * cons * OMEGA(I);
    im(I) = L * cons * OMEGA(I) * (-0.5 * ETA);

    a(I) = (exp(-im(I)) + exp(im(I))) * sin(rl(I));
    b(I) = (exp(-im(I)) - exp(im(I))) * cos(rl(I));
    c(I) = (exp(-im(I)) + exp(im(I))) * cos(rl(I));
    d(I) = (exp(-im(I)) - exp(im(I))) * sin(rl(I));
    u(I) = c(I) * rl(I) - d(I) * im(I);
    v(I) = d(I) * rl(I) + c(I) * im(I);
    h(I) = u(I)^2 + v(I)^2;

    r(I) = (a(I) * u(I) - b(I) * v(I)) / h(I);
    t(I) = (-1.0) * (a(I) * v(I) + b(I) * u(I)) / h(I);

    O(I) = E33T + N * (r(I) - 1 - ETA * t(I)) ;
    P(I) = -DELTA * E33T + N * (t(I) + ETA * r(I) - ETA);
    G(I) = -P(I) * M(I);
    B(I) = O(I) * M(I);
```

End

```
y(:,1) = f/1000;
y(:,2) = transpose(G);
y(:,3) = transpose(B);
```

```
subplot(2,1,1);
plot(f/1000,G');
subplot(2,1,2);
plot(f/1000,B');
```

```
dlmwrite('Y for free PZT_Effective.xls',y,'\t');
```

APPENDIX E

Comparison of Susceptance Signatures against Frequency Plot for Free Ended PZT Patch between Experiment, Analytical Model and Numerical Model

(a) Experimental vs. numerical (0 – 900 kHz)

(b) Experimental vs. analytical (0 – 900 kHz)

APPENDIX F

1. Stress-Strain Histories of Specimen 2 Using FBG and ESG Strain Sensors

3mm ESG

60mm ESG

50mm FBG based strain gauge

2. Measurements of ESG (60mm) and FBG (50mm) Sensor for Each Loading
Cycle from Specimen 2

3. Conductance Signatures of PZT Patch Bonded on Specimen 3 at Various Loading Stages