AN INTEGRATED APPROACH FOR STRUCTURAL HEALTH MONITORING

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By

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Submitted

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CERTIFICATE

This is to certify that the thesis entitled ‘AN INTEGRATED APPROACH FOR STRUCTURAL HEALTH MONITORING’ being submitted by Mr RAMA SHANKER to the Indian Institute of Technology Delhi for the award of the degree of DOCTOR OF PHILOSOPHY in Civil Engineering is a record of bonafide research work carried out by him under our supervision and guidance. He has fulfilled the requirements for the submission of the thesis, which is best of our knowledge, has reached the requisite standard.

The material contained in this thesis has not been submitted, in part or in full to any other University or Institute for the award of any degree or diploma.

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(Rama Shanker)
ABSTRACT

There is a phenomenal rise in construction activities in the field of civil engineering in the recent years. Major structures like buildings, bridges, dams are subjected to severe loading and their performance is likely to change with time. It is, therefore, necessary to check the performance of a structure through continuous monitoring. If performance deviates from the design parameters, appropriate maintenance is required. The life of a structure depends on initial strength and the post construction maintenance. It is for this reason that the necessity of structural health monitoring (SHM) is emphasized worldwide. There are several techniques to monitor the health of structures. These can be divided broadly into two types, global and local. The local and global techniques independently cannot monitor the health of a structure continuously in an autonomous manner. For example, the global technique, cannot determine incipient damage. The local techniques, being localized in nature, can identify damage only within a limited zone. Hence, a technique is required for structural health monitoring (SHM), which should carry out continuous monitoring of structure both locally and globally, should be sensitive and at the same time cost effective. The primary objective of this research work is to develop a new technique by integrating the global and local techniques based on piezoceramic sensors.

The global and the local techniques are studied to identify the advantages and drawbacks of each technique. It is found that the global dynamic techniques work only in low frequency range (typically < 200Hz) and can detect moderate to severe damage. However, global techniques do not detect hair line cracks which develop at an early stage. Opposite to this technique, a local technique called electro-mechanical
impedance (EMI) technique, which is based on piezo-electric ceramic (PZT) sensors; operates at higher frequency range and can typically detect damage at microscopic level. Damage can be detected at a very early stage by the EMI technique. However, the EMI technique typically fails to properly distinguish among severe damages. It is proposed to integrate EMI technique with the global dynamic techniques to take advantage of both the techniques.

There are different types of sensors which can be used for SHM. In general, the performance of PZT sensor is better than other sensors and are also very cost effective. In this study, PZT patches have been used as sensors for both global and local level damages. In addition, the possibility of an embedded PZT sensor has been investigated. The PZT sensor is embedded in structure at the time of construction. It is successfully demonstrated that the embedded patch acts as sensors for both the global dynamic technique and the EMI technique.

Detection of incipient damage is quite critical for the challenging task for health monitoring of structures. In this study, through artificial damage created in the structures, it is found that the incipient level damage is very quickly detected by the EMI technique. For moderate to severe damages, the same PZT is capable of serving as the sensor of the global dynamic technique, and can suitably quantify such damages as well as locate them. Hence, PZT patches, which have so far been used largely with EMI technique, have been found suitable for global techniques in this study.
A simple low cost experimental technique has been developed to extract the experimental strain mode shapes of the structures. Experimental mode shapes extracted using the proposed technique require less interpolation and are obtained using a single PZT sensor. Resolution of measurement can be adjusted as per desired accuracy. The technique uses a surface bonded or embedded PZT sensor to extract the experimental strain mode shape directly. Damage ranging from incipient to near failure (severe) can be located and quantified using the EMI technique and the experimental mode shapes with desired accuracy. Incipient damage is located using extracted equivalent parameter from the admittance signature of different sensors. Moderate to severe damages are located using extracted experimental mode shape. Basic advantage of the combined technique is that location of damage can determined out with desired accuracy.

The conventional methods, which differentiate the damage as incipient, moderate and severe, are based on experience. A new algorithm has been developed to determine the severity of damage using experimental mode shapes. The basic advantage of the algorithm is that the severity of the damage can be computed in terms of the original stiffness of structure.

It has also been shown that by suitable integration of the global dynamic and the EMI technique with artificial neural networks (ANN), the issues of localization and quantification can be addressed more appropriately. Hence, the integration of these techniques leads to much more effective SHM and this forms the main contribution of the thesis.
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LIST OF SYMBOLS

A  Area
B  Raw susceptance
B_A,  Active susceptance
B_P  Passive susceptance
c  Damping constant
[C]  Damping matrix
D_1, D_2, D_3  Surface charge density across surfaces normal to 1, 2, 3 axes respectively
\( d_{31} (d_{1k}) \)  Piezoelectric strain coefficient of PZT patch corresponding to axes 3(i) and 1(k)
E  Young’s Modulus of the material
E_3 (E_i)  Electric field along axis 3 (i) of PZT patch
[E]  Electric field vector
f  Frequency
F  the force vector
G  Raw conductance
G_A  Active conductance
G_P  Passive conductance
h  Thickness of PZT patch
I  Moment of Inertia
j  \( \sqrt{-1} \)
k  Spring constant
[K]  Stiffness matrix
l  Half-length of PZT patch
m  Mass
M  Bending moment
[M]  Mass matrix
S_1 (S_i)  Mechanical strain along axis 1 (i)
S_g  Gauge factor
T_1 (T_i)  Mechanical stress along axis 1 (i) of PZT patch
<table>
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<tr>
<td>( \bar{T} )</td>
<td>Complex tangent function</td>
</tr>
<tr>
<td>u</td>
<td>Displacement</td>
</tr>
<tr>
<td>V</td>
<td>Strain Energy</td>
</tr>
<tr>
<td>( \bar{V} )</td>
<td>Complex electric voltage</td>
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<td>( w_p )</td>
<td>Width of PZT patch</td>
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<td>x</td>
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<tr>
<td>( x_a )</td>
<td>Real part of the mechanical impedance of PZT patch</td>
</tr>
<tr>
<td>y</td>
<td>Imaginary part of the mechanical impedance of structure</td>
</tr>
<tr>
<td>( y'' )</td>
<td>Curvature (second derivative of displacement)</td>
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<tr>
<td>( y_a )</td>
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<td>( \bar{Y}_p )</td>
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<tr>
<td>( Z_a )</td>
<td>Complex Mechanical impedance of PZT patch (( Z_a = x_a + y_aj ))</td>
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<tr>
<td>( \varepsilon_{33}^{\bar{T}} )</td>
<td>Complex permittivity of PZT patch along axis 3 at constant stress</td>
</tr>
<tr>
<td>( \omega )</td>
<td>Angular frequency (rad/s)</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Dielectric loss factor</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Material density</td>
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<tr>
<td>( \eta )</td>
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<td>( \phi )</td>
<td>mode shape function</td>
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<td>Mode shape matrix</td>
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<td>( \rho )</td>
<td>Material density</td>
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**Subscripts**

- A: Active
- eff: Effective
- o: Amplitude of a quantity
- eq: Equivalent; Equilibrium
f, free Free
i Imaginary
P Passive
p Relevant to PZT patch
qs Quasi-static
r Real
res Resultant
1,2,3 or x,y,z Coordinate axes
# LIST OF ACRONYMS

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<td>Artificial Neural Networks</td>
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<tr>
<td>CVR</td>
<td>Cockpit Voice Recorder</td>
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<td>DOF</td>
<td>Degrees Of Freedom</td>
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<td>DI</td>
<td>Damage Index</td>
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<td>ESG</td>
<td>Electrical Strain Gauges</td>
</tr>
<tr>
<td>FBG</td>
<td>Fibre Bragg Grating</td>
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<td>FDR</td>
<td>Flight Data Recorder</td>
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<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>HHT</td>
<td>Hilbert–Huang Transforms</td>
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<td>IDT</td>
<td>Inter Digital Transducers</td>
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<tr>
<td>LCR</td>
<td>Inductance (L) Capacitance (C) Resistor (R)</td>
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<tr>
<td>MAC</td>
<td>Modal Assurance Criteria</td>
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<td>MS</td>
<td>Mild Steel</td>
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<td>MSD</td>
<td>Multiple Site Damage</td>
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<td>MSE</td>
<td>Mean Squared Error</td>
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<td>NDE</td>
<td>Non-Destructive Evaluation</td>
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<td>NSINs</td>
<td>Neural System Identification Networks</td>
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<td>PZT</td>
<td>Piezo-Electric Ceramic</td>
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<td>RBES</td>
<td>Rule Based Expert System</td>
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<td>RC</td>
<td>Reinforced Concrete</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>RMSD</td>
<td>Root Mean Square Deviations</td>
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<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>SHM</td>
<td>Structural Health Monitoring</td>
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<tr>
<td>STRECH</td>
<td>Structural Translational and Rotational Error Checking</td>
</tr>
<tr>
<td>TNN</td>
<td>Traditional Neural Network</td>
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CHAPTER 1

INTRODUCTION

1.1 STRUCTURAL DAMAGES AND FAILURES
There is continuous deterioration of strength after construction of any civil, mechanical and aerospace structure due to loading and environmental impacts. Structures consist of an assembly of various members like columns, beams, slabs etc. At the construction time, it is impossible to ensure a uniform quality and strength at every section. Hence, there is variation of strength from section to section. However, if this variation is under a certain threshold limit, structure can be considered to be damage free. If this variation increases beyond the threshold limit due to certain reasons like excessive loads or fatigue, it would result into damage. If again this limit increases and crosses certain value, it can be said that the element has failed. Hence, damage and failure are relative terms and vary from structure to structure. For example, in case of aerospace structure, failure threshold is much lower as compared to civil structures.

Damage is defined as a change to the material and/ or geometric properties of the structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system’s performance (Farrar and Warden, 2007). In most general term, ‘failure’ refers to any action leading to an inability on the part of a structure or machine to function in the intended manner (Ugural and Fenster, 1995). Yao (1995) defined the term damage as a deficiency or deterioration in the strength of the structure, caused by external loading or environmental conditions or human errors. Structural failure refers to loss of the load-carrying capacity of a component or member within a
structure or of the structure as a whole beyond a threshold. The ultimate failure strength of the material, component or system is its maximum load-bearing capacity. When this limit is reached, damage in the materials occurs, and its load-bearing capacity is reduced permanently, significantly and quickly. In a well-designed system, a localized failure should not cause immediate or even progressive collapse of the entire structure. Ultimate failure strength is one of the limit states that must be accounted for in structural engineering and structural design. To avoid collapse/accident, localized damage should be detected timely for taking appropriate measure.

1.2 RECENT ACCIDENTS DUE TO STRUCTURAL FAILURE

A 150 year-old bridge near the Bhagalpur railway station in the Indian state of Bihar collapsed on December 2, 2006 when a train was passing, as shown in Fig. 1. Thirty people were killed and several others injured. Investigation committee found that life of bridge was over and no monitoring was done about remaining strength and serviceability. It was also noted that the bridge was poorly maintained.

Fig. 1.1 Collapse of Railway Bridge near Bhagalpur (http://www.outlookindia.com)
The Val di Stava dam collapsed on July 19, 1985 which resulted in one of Italy's worst disasters. The upper dam collapsed first, which resulted in the collapse of the lower dam also. Around 200,000 cubic meters of mud, sand and water were released into the Rio di Stava valley towards the village of Stava at a speed of over 90 km/h. It resulted, in the death of 268 people, destruction of 62 buildings and demolition of eight bridges. Investigation committee found that the dam was poorly maintained and the margin of safe operation was very small.

On August 01, 2007, the main span of 1907 - foot bridge collapsed and fell into Mississippi River and onto its banks as shown in Fig.1.2. Thirteen people died and approximately one hundred more were injured. It was found that the bridge was loaded with additional dead load caused by the addition surface coating at time of repairing. Unfortunately the stress level was not checked after addition of this extra surface coat.

![Fig. 1.2 Collapse of Bridge on Mississippi River (http://www.blogrunner.com)](http://www.blogrunner.com)
On 25 May 2002, Boeing 747-209B B-18255 was scheduled to fly flight CI 611 Taipei-Hong Kong. The aircraft broke into pieces in mid air and all the passengers and the crew members were killed. The final investigation report (http://aviation-safety.net) found that the accident was the result of metal fatigue due to inadequate maintenance after a previous incident of tail strike in 1980. Evidence of fatigue damage was found in the lower aft fuselage near the outer row of the securing rivets. Multiple Site Damage (MSD), including a 15.1-inch through thickness main fatigue crack and some small fatigue cracks were confirmed. The 15.1-inch crack and most of the MSD cracks initiated from the scratching damage associated with the 1980 tail strike incident. Further, residual strength analysis indicated that the main fatigue crack in combination with the MSD were of sufficient magnitude and distribution to facilitate the local linking of the fatigue cracks so as to produce a continuous crack within a two-bay region (40 inches). Ironically, none of the maintenance inspection of B-18255 could detect the ineffective 1980 structural repair and the fatigue cracks that were developing gradually.

1.3 STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) is a process in which certain strategies are implemented for determining the presence, location and severity of damages and the remaining life of structure after the occurrence of damage. This term is usually referred to aerospace, civil and mechanical engineering infrastructure. It is the continuous measurement of the loading environment and the critical responses of a structural system or its components. Health monitoring is typically used to track and evaluate the
performance, symptoms of operational incidents and anomalies due to deterioration or damage as well as health during and after extreme events (Aktan et al. 1998). Damage identification is the basic objective of SHM.

There are mainly four levels in damage identification (Rytter, 1993):

Level 1: Determination that damage is present in the structure

Level 2: Level 1 plus determination of the geometric location of the damage

Level 3: Level 2 plus quantification of the severity of the damage

Level 4: Level 3 plus prediction of the remaining service life of the structure

SHM involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of the system health. For long term SHM, the output of this process is periodically updated to provide information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for quick condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure (Doebling et al., 1998).

Health monitoring has gained considerable attention in the civil engineering community over the last two decades. Although health monitoring is a maturing concept in the manufacturing, automotive and aerospace industries, there are a number of challenges for effective applications of the concept on civil infrastructure systems. While successful
real-life studies on new or existing structures are necessary for transforming health monitoring from research to practice, laboratory benchmark studies are also essential for addressing issues related to the main needs and challenges of SHM. Although it is still mainly a research area in civil infrastructures, it would be possible to develop successful real-life health monitoring systems if all components of a complete health design are recognized and integrated. Hence, SHM offers great promise for civil infrastructure implementations.

1.4 NEED OF SHM

Appropriate maintenance prolongs the life span of a structure and can be used to prevent catastrophic failure. Higher operational loads, complexity of design and longer life time periods imposed to civil structure make it increasingly important to monitor the health of these structures. Economy of a country depends on the transportation infrastructures like bridges, railways, roads etc. Any structural failure of these causes severe damage to the life and economy of the nation. Every nation is spending millions of Dollars every year for the rehabilitation and maintenance of civil engineering structures. Failure of civil infrastructure to perform at optimum level may effect the gross domestic production of the country. Strength of structures decreases due to continuous loading and impact of environment. Hence, it should be evaluated if the performance of the structure is satisfactorily or not after such deterioration. If structural strength falls down below a certain threshold level, sudden failure is possible which might result in accident and affect the serviceability of the structure. Early detection of damage is of special concern for civil structures. If not identified in time, damage may have serious consequences for
safety of occupants. There are several natural events which may affect the strength of structure. It should be ensured that the structure is safe after such natural events. If structures are monitored periodically or continuously, better understanding will be achieved about the behaviour of the structure. It will be very useful for design improvement. By proper SHM, the number of catastrophic events can be decreased, which will be helpful for economy of the country and also for psychology of human beings. If damage/ cracks developed before failure, are detected at an early stage, proper measures can be taken. Collapse of bridges, tall buildings and other important structures hamper the economic growth of the country and also results in the loss of human resources. Structures are designed for a certain life span, and it is assumed that during this period the structure is maintained properly. By proper monitoring, it may be possible that the life of the structure be increased and serviceability enhanced, resulting in huge savings. Fatigue assessment can be determined, if continuous monitoring is done. It may possible that a new constructed structure may not be performing well with respect to design parameters, either due to inferior material or faulty construction. This can be ensured by proper health monitoring.

A successful health monitoring design requires the recognition and integration of several components. Identification of health and performance metric is the first component which is a fundamental knowledge need and should dictate the technology involved. These facts underline the importance of an automated health monitoring system, which can not only prevent an incipient damage included collapse, but also make the assessment of structural health, as and when desired, at a short notice. These automated systems hold the promise
for improving the performance of the structure with an excellent benefit/cost ratio, keeping in view the long term benefits.

1.5 SHM TECHNIQUES

Until very recently and to great extent even today, visual inspection by trained personnel had been the most common tool to identify the external signs of damage in buildings, bridge and industrial structures. Once gross assessment of the damage location is made, localized techniques such as acoustic, ultrasonic, radiography, eddy currents, thermal, magnetic field or electro-magnetic impedance can be used for a more refined assessment of the damage location and severity. If necessary, test samples may be extracted from the structure and examined in the laboratory. One essential requirement of this approach is the accessibility of the location to be inspected. In several cases, critical parts of the structure may not be accessible or may need removal of finishes. This procedure of health monitoring can therefore be very tedious and expensive. Also, the reliability of the visual inspection is dependent, to large extent, on the experience of the inspector.

Over the last three decades, a number of studies have been reported which strive to replace the visual inspection by some sort of automated method, which enable more reliable and quicker assessment of the health of the structure. The idea of smart structures was thought to be an alternative to the visual inspection methods. Because of their inherent ‘smartness’, the smart materials (such as piezoelectric material, shape memory alloys, fibre optic materials) exhibit high sensitivity to any change in environment.
1.5.1 SHM BY GLOBAL DYNAMIC TECHNIQUES

In these techniques, the test-structure is subjected to low-frequency excitations, either harmonic or impulse, and the resulting vibration responses such as displacements, velocities or accelerations are picked up. First few mode shapes and the corresponding natural frequencies of the structure are determined, which, when compared with the corresponding data of healthy state, yield information pertaining to the locations and the severity of the damage. Damage in a structure alters its modal parameters, such as modal frequencies, modal damping, and mode shape. Changes also occur in structural parameters, namely the stiffness and the damping matrices. Health of structure is judged after comparing the current structural parameters with the baseline parameters. However, the basic drawback of this technique is low sensitivity to incipient damage.

1.5.2 SHM BY ELECTROMECHANICAL IMPEDANCE (EMI) TECHNIQUE

In the EMI technique, a piezoelectric ceramic (PZT) sensor patch is bonded/embedded in the structure (whose health is to be monitored) using high strength epoxy adhesive. The conductance signature of the patch is acquired over a high frequency range (30-400 kHz). This signature forms the benchmark for assessing the structural health. At any future point of time, when it is desired to assess the health of the structure, the signature is acquired again and compared with the benchmark signature. The signature of the bonded PZT patch is usually acquired by means of commercially available impedance analyzers/ LCR meters. The impedance analyzer/ LCR meter imposes an alternating voltage signal of 1 volts R.M.S. (root mean square) to the bonded/ embedded PZT transducer over the user specified preset frequency range. The magnitude and the phase
of the steady state current are directly recorded in form of the conductance and the susceptibility of signatures in the frequency domain, thereby eliminating the requirements of domain transforms.

This research work carried out with objective of integration of EMI technique with global dynamic techniques for expanding the SHM capabilities of piezo-sensors. The following sections highlight the objectives and contributions to the SHM.

1.6 RESEARCH OBJECTIVES

There are several global and local techniques for SHM. A local health monitoring technique (such as the EMI technique) monitors the structural health only locally and also it may be possible that it fails to distinguish moderate and severe damages. On the other hand, if any global technique (such as global vibration techniques) is used, it does not detect the incipient damage. Hence, it is difficult to monitor the health of structure completely using a single existing technique. So far, altogether different sensors are used for the two approaches: global and local.

The primary aim of this research work was to integrate the local EMI technique with global vibration technique, using the same PZT sensor as the common sensor for both. So that it is able to monitor the health of structure continuously and could be at same time cost effective. It is also aimed to quantify damage more rationally using the indices of both the global and local approach concurrently. The specific objectives were:

(1) To evolve a new integrated technique to monitor the complete health of structures by combining the EMI technique with the global vibration technique, such that the
same PZT patch plays the role of sensor for each technique, with minimum additional hardware requirements.

(2) To develop a low cost experimental technique to extract the strain mode shapes of the structures directly using PZT sensors.

(3) To utilize the EMI technique for detecting and locating incipient damage and determine the damage location and severity for moderate and severe damage using the experimental mode shapes and frequency changes (global parameter), obtained from surface-bonded or embedded PZT patches.

(4) To utilize artificial neural network for more efficient learning and data processing for reporting damage location and severity based on input data.

1.7 RESEARCH ORIGINALITY AND CONTRIBUTIONS

This research has successfully integrated the global dynamic technique with the EMI technique utilizing the same PZT patch as the key element. A low cost experimental technique has been devised to extract the strain mode shapes of the structures directly. The technique uses single surface bonded or embedded PZT sensor. The same PZT patch can be used as a sensor in both global dynamic and the EMI techniques. An embedded PZT sensor was also investigated; this can be embedded in reinforce concrete (RC) structure at the time of construction. It is successfully demonstrated that the lower modes can be derived using the PZT patches. An integrated SHM approach has been proposed for implementation in real-life situations by combining the EMI and global techniques. Proposed approach is more sensitive and cost effective compare to conventional techniques. Presence, severity and the location of damage/crack can be determined
accurately using this approach. Both the techniques compliment each other. Approximate remaining life of structure after damage can also be predicted using the combined technique. Hence, it provides a better tool of SHM. The proposed new approach is able to monitor the complete health of structures.

1.8 THESIS ORGANISATION

This thesis consists of a total of eight chapters including this introductory chapter. Chapter 2 presents a detail review of state-of-the-art in SHM, descriptions of the global dynamic techniques, concept of smart systems and materials and the EMI technique and brief review of ANN. Chapter 3 covers the descriptions and comparisons of different type of sensors that are used for response measurement of structures. In Chapter 4, detailed procedure to detect the presence of incipient damage using EMI technique and moderate to severe damage using global dynamic technique are covered. Chapter 5 presents the extraction of experimental strain mode shapes using a single PZT patch. Location of damage is determined using the experimental mode shapes in case of moderate to severe damage. This is validated on an ISMB 150 steel beam and MS plate. Chapter 6 deals the computation of damage severity in term of original stiffness. An analytical expression is derived for damage severity. Finally, it validated on the ISMB 150 steel beam and mild steel (MS) plate. In Chapter 7, practical application of integrated approach has been covered on an RC frame. Finally, conclusions and recommendations are presented in Chapter 8, which is followed by a list of author’s publications and a comprehensive list of references.
CHAPTER - 2

LITERATURE REVIEW

2.1 INTRODUCTION

There are various approaches for addressing the problem of health monitoring and damage detection in structures. The basic principle utilized is that any flaw/ damage changes some characteristic and hence the response of the structure. Researchers have proposed several techniques based on different kinds of structural characteristics or responses. The various methods reported in the literature can be broadly classified into the following categories:

(i) Global techniques

(ii) Local techniques

2.2 GLOBAL TECHNIQUES

Global technique can be classified into two categories:

(a) Global static response based techniques

(b) Global dynamic response based techniques

2.2.1 Global Static Response Based Technique

A technique based on static displacement response was formulated by Banan et al. (1994). The technique involves applying static forces on the structure and measuring the corresponding displacements. It is not necessary to select entire set of force and displacements. Any convenient subset may be selected. However, several load cases
might be necessary to obtain sufficient information. The resulting equations are solved recursively to arrive at a set of member constitutive properties or the structural parameters. Any change in parameters from the baseline healthy state gives the indication of the presence of damage.

The technique has a number of shortcomings, especially in the way of practical implementation. Measurement of displacements on a large real-life structure is not an easy task. As a first step, one needs to establish a frame of reference which requires the construction of a secondary structure on an independent foundation. In addition, employing a number of load cases and computational approach can be very time-consuming.

Sanayai and Saletnic (1996) proposed a similar technique based on static strain measurement. The advantage of this technique over the previous one is that strain measurement can be made with a much higher degree of precision. In addition, the establishment of an independent frame of reference is also circumvented. Strain on a structure’s surface is caused by both bending and axial deformations, and is therefore able to capture the element behaviour well. However, like the displacement approach, this technique is also based on the least squared minimization of strain error function. Therefore, the approach faces similar computational problems. In addition, its application on real life structures is bound to be very tedious.
The application of large loads to cause measurable deflections (or strain) may necessitate huge machinery and power input. As such, these methods are too tedious and expensive to enable a timely and cost effective assessment of the health of real life structures.

2.2.2 Global Dynamic Response Based Techniques

The main principle of these techniques is that the modal parameters like the frequencies, the mode shapes and the modal damping are functions of the physical properties of the structure like mass, damping and stiffness. Hence, any change in the physical properties resulting from damage will cause detectable change in the modal parameter. Depending upon the modal parameter employed, these technique can be divided into four types:

1. Based on frequency changes
2. Based on mode shape change
3. Based on modal damping change
4. Based on updating structural model parameter

2.2.2.1 Frequency Change

Considering frequency change as a parameter for damage detection, Salawu (1997a) presented a comprehensive review. Since modal frequency is a global parameter, its value depends upon the sum total of properties at each point of the structure. On the other hand, damage is a local phenomenon, limited only to specific region of the structure. In case of incipient damage, only very small area is affected and resultant overall change in the natural frequency therefore become negligible. Hence, this method fails to detect the incipient damage. Another drawback of the technique is, for the same level of damage,
change in the frequency could be different depending upon damaged region. Also, alone the frequency changes can not provide spatial information about damage.

Cawley and Adams (1979) were the first researchers to apply frequency shift method to detect the damage in a composite material. They considered a parameter based on ratio of frequency shifts of two different modes. Further, Stubbs and Osegueda (1990) extended this work and developed a damage detection method using the sensitivity of modal frequency change.

It is found that for same level of damage in congruent structures, changes in frequencies are different. This is one of the major draw back of the techniques based on frequency changes. Reason of this phenomenon is that for same level of damage at a point, the type of damage may be different. It may be possible that existence of damage at that place may affect several other parts, so that change of frequency might depend upon the loss of stiffness of others points. If the damage becomes very severe, others points are also affected substantially, hence change in frequencies will be significant. Surely, for same level of damage, damage created artificially and other created by application of load, will lead to different frequency changes.

2.2.2.2 Mode Shape Change

The techniques relying on mode shape changes can be divided into two categories:

1. Displacement mode shape change
2. Curvature/ strain mode shape change
2.2.2.1 Displacement Mode Shape Change

West (1984) was the first researcher to use the mode shape information for detection and location of structural damage using the modal assurance criteria (MAC). The mode shapes were partitioned using various schemes, and the change in MAC across the different partitioning techniques was used to localize the structural damage. Mayes (1992) presented a method to detect damage based on mode shape changes known as structural translational and rotational error checking (STRECH). In this method, ratios of relative modal displacements was determined, STRECH assesses the accuracy of the structural stiffness between two different structural degrees of freedom (DOF). STRECH can be applied to compare the results of a test with an original FEM or to compare the results of two tests. Fox (1992) created artificial cut in a beam and measured the MAC. He reported that MAC is relatively insensitive to damage. “Node line MAC”, a MAC based on measurement points close to a nodal point for a particular mode, was found to be a more sensitive indicator of changes in the mode shape caused by damage. Graphical comparisons of relative changes in mode shapes proved to be the best way of detecting the damage location when only resonant frequencies and mode shapes were examined (Doebling et al. 1998).

2.2.2.2.2.1 Curvature /Strain Mode Shape

An alternative to the displacement mode shape is the curvature mode shape for damage detection. Basic principle of this approach is based on the relationship between curvature and the flexural stiffness of a beam. If the flexural stiffness of the beam decreases, the curvature increases. In case of a PZT patch surface bonded on structure, curvature mode shape is directly obtained since the voltage response across the patch is directly proportional to strain, and hence curvature. Several publications discussed the practical issue related to event of measure strain directly or computing it from displacements or accelerations. Some related publications are given below:

(1) Panday et al. (1991) obtained curvature mode shape by displacement mode shape using central difference method.

(2) Chance et al. (1994) presented an experimental device for simulating crack in beam and plate. A groove was machined into beam and two blocks were inserted into the groove. The two pieces were designed to open and close like a fatigue crack, which demonstrated bilinear stiffness. Their experiments on a cantilever beam with the device and a cantilever plate with a hole showed that the curvatures were locally sensitive to the fault but mode shapes were not.

(3) Stubbs and Kim (1996) examined the feasibility of localizing damage using curvature mode shape without baseline modal parameters.

(4) Zhou et al. (2007) used strain mode shapes obtained from a pair of strain gauges bonded on the extremes of beam.
2.2.2.2.2 Limitations of Curvature/Strain Mode Shape

1. The location of damage can be predicted with accuracy the distance between sensors. It is not practically to install the sensors at each point of structure (Zhou et al., 2007).

2. The location of damage can be predicted accurately, if experimental stain mode shapes are used in prediction. However it is difficult to extract it.

2.2.2.3.1 Modal Damping Change

Damping exists in all vibratory systems whenever there is energy dissipation. This is true for each civil structure even though most are inherently lightly damped. For free vibration, the loss of energy from damping in the system results in the decay of the amplitude of motion. In forced vibration, loss of energy is balanced by the energy supplied by excitation. Modal damping increases with damage; hence it can be used as indicator of damages, but it is very difficult to measure accurately. The use of damping ratio for damage detection is found rarely in literature, but it can be used as supplement parameter for damage detection with the other major variable like frequencies, mode shapes, strain energy etc. Following are some of the literature related to this aspect:

1. Salane and Baldwin (1990) tested a steel girder bridge with concrete decking. They found that no rational relation between damping ratios and damage. Damping ratio initially increased and subsequently decreased with damage severity.

2. Casas and Aparicio (1994) tested on partially cracked concrete beams. They also found no clear relation between crack growth and damping ratio. Farrar and Jauregui (1998) also found that damping of a steel plate girder bridge did not consistently increase or decrease with increasing damage.
3. Modena et al. (1999) presented two techniques based on damping for local damage measurement. The first was based on the variation of an energetically equivalent modal damping ratio, the second one on distinguishing the contribution of a viscous and friction component in damping and identifying the damage through friction detection and characterization.

4. Ndambi and Antomme (2002) used of damping as indicator for damage detection and damping ratio was determined by using energy method. The proposed method was applied on cracked RC beams.

2.2.2.3.1 Limitations of Modal Damping Change

1. It is difficult to evaluate the damping ratio of a structure.

2. There is minor or negligible change in damping ratio in case of hair line crack or initial damage.

3. Modal damping is a global property. Hence, it is insensitive for local damage.

2.2.2.4 Updating Structural Model Parameters

The fundamental principle of model updating method is based on the perturbation of the mass, the stiffness, and the damping matrices (estimated ones) such that the response of resulting model resembles the measured data of real structure. Hence, the damage can be detected by comparing the updated structural properties of model and the original one. The finite element model updating is a very wide term, and it has no universal rule for updating. It has certain specific objectives for updating and updated model resembles only that specific objective. It can be explain in terms of following aspect. Suppose a model of a structure is updated for damage detection. If the structure is damaged, its
structural properties like mass, stiffness, and damping change. Hence, these parameters are perturbed in model such that measured parameters like displacement, velocity and acceleration from original structure is close to test of the model. It is possible that other parameters may be differing. There are generally three method of updating structural parameters, namely:

1. Optimum matrix update method
2. Sensitivity based updating method
3. Eigen structure assignment method

Several publications related to model updating based on above methods are reported. Brownjohn and coworkers have successfully applied the model updating approach for condition assessment of several real-life highway bridges (Xia and Brownjohn, 2003; Brownjohn et al. 2003; Brownjohn et al. 2005). Tu and Lu (2003) proposed a novel updating approach based on genetic algorithms. However, model updating for damage detection is not the primary concern in this thesis.

2.2.2.4.1 Advantages of Model Updating

1. The presence, locations and severity of damage can be determined after structural model updating.
2. It can be used as the data base for future evaluation of the structures.
3. The change in structural behaviour of structure after damage can be also estimated by model updating.
4. Determination of other responses of the structure like deflection etc. is also possible by model updating.
2.2.2.4.2 Limitations of Model Updating

There are several limitations of model updating, some of which are listed below:

1. Determination of the presence, location, and severity of damage by using model updating are not reliable. It is found in several cases that it gives wrong result after model updating. Hence, it is not very reliable method for health monitoring.

2. A lot of mathematical calculations are required for model updating. Hence, method is lengthy and tedious.

3. Model updating is not a generalized method. Each structure requires own model updating. Hence, a lot of studies required before application of this method to apply on the structure.

4. The behaviour of structure can be simulated only in certain specific chosen parameter. For example, after model updating, natural frequencies of model and actual structure might be same however, displacement at a point of model and structure may differ. Hence, others parameters of structure may be different from model’s prediction.

5. A lot of measurements are required for model updating. Hence, application of this method can not be possible by unskilled person.

6. There is requirement of measurement data of the intact structure for model updating. Usually this data are not available in practice.

7. It is impossible to measure all the modes by model updating. It depends upon the number of measurements have been taken.
2.3 TECHNIQUES BASED ON SPECIFIC STRUCTURAL PARAMETERS

Apart from the above techniques, there are other variants of global dynamic techniques based on the fact that structural parameters which change with damage. Some prominent algorithms of this category are described below.

2.3.1 Stiffness Changes

Zimmerman and Kaouk (1994) proposed “change in stiffness method” based on changes in stiffness resulting from damage. This method identifies changes in structural stiffness matrix resulting from damage. The stiffness matrix $[K]$ is determined from the mode shapes and the modal frequencies derived from the measured dynamic response of the structure, as

$$[K] = [M][\Phi][\Omega][\Phi]^T[M] = [M]\left(\sum_{i=1}^{n} \omega_i^2 \Phi_i \Phi_i^T\right) [M] \quad (2.1)$$

where, $[M]$ is the mass matrix, $[\Phi]$ the mode shape matrix and $n$ the total number of modes considered. Let $[\Delta K]$ represents the change in stiffness matrix due to damage. The indicator of damage in this method is a damage vector defined by

$$[D_i] = [\Delta K][\Phi_i] \quad (2.2)$$

where, $[D_i]$ is the $i^{th}$ damage vector, obtained from the $i^{th}$ mode shape vector $[\Phi_i]$. The location of the damage is indicated by the row of the maximum parameter in the damage vector.
This method has a significant drawback. Higher modes are important in the estimation of the stiffness matrix, as can be seen from Eq. (2.1). Since, modal contribution to $[K]$ increases as the modal frequency increases. Unfortunately, the dynamic vibration testing can yield only first few mode shapes. Hence, the estimated $[K]$ is likely to be inaccurate.

### 2.3.2 Flexibility Changes

Pandey and Biswas (1994) were the first to propose the change in flexibility method. The basic principle in this approach is that damage in the structure alters its flexibility matrix, which can be used to ‘identify’ damage. The relative amount by which the various elements are altered is used to ‘localize’ the damage. Like the change in stiffness method, mode shape vectors and resonant frequencies obtained from the dynamic response data (collected before damage and after damage) are used to obtain the flexibility matrices $[F]$, which may be expressed as

$$
[F] = [\Phi] \left[ \Omega \right]^{-1}[\Phi]^T = \sum_{i=1}^{n} \left( 1 + \omega^2 \right) \Phi_i \Phi_i^T
$$

(2.3)

As can be seen from Eq. (2.3), $[F]$ is proportional to the square of the inverse of the modal frequencies. Therefore, it converses rapidly with increasing frequencies. Hence, only a few lower modes are sufficient for accurate estimation of $[F]$. The maximum of the values at a particular column $\delta_j$ of $[F]$ is taken as an index of flexibility for that particular degree of freedom. Any change in this parameter is regarded as an indicator of
damage at that particular degree of freedom. In the case of a simply supported beam, the change is maximum at the damaged element. The amount of change is a measure of the severity of damage. Although the technique is an improvement over the change in stiffness method, the researchers did not investigate the case of multiple damage locations.

Aktan et al. (1994) suggested the use of measured flexibility as a structural condition to assess the relatively integrity of a bridge. They compared the measured flexibility of the bridge to the static deflection induced by a set of truck load tests.

2.3.3 Technique based on strain energy

Stubbs and Kim (1994) developed the damage index method. The damage index $\beta$ is calculated based on the strain energy stored in the structure when it deforms in particular mode shape. For the $j^{th}$ location and the $i^{th}$ mode, the damage index $\beta_{ij}$ is defined as

$$
\beta_{ij} = \frac{\left(\int_{a}^{b} [\Phi_i(x)]^2 dx + \int_{0}^{L} [\Phi_j'(x)]^2 dx \right) \int_{0}^{L} [\Phi_i(x)]^2 dx}{\left(\int_{a}^{b} [\Phi_i(x)]^2 dx + \int_{0}^{L} [\Phi_j'(x)]^2 dx \right) \int_{0}^{L} [\Phi_i'(x)]^2 dx}
$$

(2.4)

where, $\Phi_i(x)$ and $\Phi_i''(x)$ are the second derivatives of the $i^{th}$ mode shape corresponding to the undamaged and the damaged structures, respectively. Here, $a$ and $b$ are the limits of a segment of a beam where damage is being evaluated. This technique has an
advantage over other techniques (such as stiffness/ flexibility approaches) in that it has specific criteria for determining whether damage has occur at a particular location.

Farrar and Jauregui (1998) did a comparative study of the above algorithms on a single structure, the I-40 Bridge over Rio Grande in Albuquerque, New Mexico, USA. The bridge had a maximum span length of about 50 m and girder depth of about 3m. Damage was induced by means of a torch cut, at the middle of the 50 m span and starting from the mid depth of web as a 600 mm long by 10 mm wide crack. It was then extended in three stages to the entire bottom half of the web and the bottom flange. The bridge was excited by a hydraulic shaker (both in undamaged and damaged conditions) to obtain the natural frequencies and the mode shapes.

The major conclusions drawn by Farrar and Jauregui based on the analysis of the response data by various methods are as follows:

1. Standard modal properties such as mode shapes and resonant frequencies are poor indicators of damage. No noticeable change in the measured resonant frequencies and mode shapes (drawn through interpolation) was observed until the final level of damage.
2. All the methods identified the damage location correctly for the most severe damage case only.
3. In some of the methods, human judgment was required to correctly identify the location of damage. If they were applied blindly, it would have been difficult to locate the damage.
4. When the entire sets of tests are considered, the damage index method is the one with the best performance.

5. Exact location of the damage cannot be predicted using any method.

Several other related publications can be found, reporting the use of improved algorithms, modern wireless technology and high speed data processing (Singhal and Kiremidjian, 1996; Skjærbaek et al., 1998; Pines and Lovell, 1998; Aktan et al., 1998, 2000; Lynch et al., 2003a). However, in spite of rapid progress in the hardware and software technologies, basic principle remain the same, which is to identify changes in the modal and structural parameters (or their derivatives), resulting from damages.

2.4 LIMITATIONS OF GLOBAL TECHNIQUES

Some of the critical issues associated with the global techniques are summarized below:

1. These techniques are dependent on the prior analytical models and/or prior test data for detection and location of the damage. If these data sets are unavailable, they are impractical. It is very difficult to generate the original data of the existing structures.

2. These techniques are based on linear structural model. Behaviour of structure can be assumed linear for small loads, it is however far from linear at failure level. Generally damage develops in structure at higher load.

3. To monitor the health of very large and heavy structures like bridges and tall building, number and location of sensor may be very large and are critical issues.
4. For small incipient level damages, it is very difficult to discriminate between changes in the modal properties resulting from damage and those changes resulting from variations in the measurements.

5. These techniques typically rely on the first few modes and the corresponding natural frequencies of the structures, which, being global, are not sensitive enough to be altered by localized incipient damages. It is for this reason that Farrar and Jauregui (1998) found that the global dynamic technique failed to identify damage location for less severe damage scenarios in their experiment. It could be possible that damage, just large enough to be detected by global dynamic techniques, is already critical for the structure in question.

6. These techniques demand expensive hardware and sensors, such as inertial shakers, self-conditioning accelerometers and laser velocity meters. For a large structure, the overall cost of such sensor systems could easily run into millions of dollars.

7. A major limitation of these techniques is the interference caused by the ambient mechanical noise, besides the electrical and the electromagnetic noise associated with the measurement systems. Incidentally, the ambient noise also happens to be in the low frequency range.

8. The pre-requisite of a high fidelity ‘model’ of the test structure restricts the application of the methods to relatively simple geometrics and configurations only. Because evaluation of stiffness and damping at the supports (which are often rusted during service), is extremely difficult, reliable identification of a ‘model’ is quite difficult in practice.
9. Often, the performances of these techniques deteriorate in multiple damage scenarios (Wang et al., 1998).

2.5 NEED FOR FURTHER RESEARCH IN GLOBAL TECHNIQUE

The following points highlight the need for further work in global dynamic techniques:-

1. The global dynamic techniques are dependent on prior test data or prior analytical/numerical models to detect and locate the damage. It is impossible to predict the health of structure, if healthy state data/undamaged data are not available. Comprehensive research is needed to get rid from dependency from prior set data.

2. All damage-identification methods based on vibration based techniques rely on linear structural models. A research is needed to account for the effect of non linearity.

3. There is uncertainty about the number and place to install the sensors to successfully detection and prediction the location of damage of real structure. Comprehensive research is needed about minimum number of sensor required for successful implementation of technique in the field. The location of sensors should not require knowledge of the damage location.

4. The global vibration techniques are unable to detect the incipient damage. Their response is poor in case of moderate damage also. Due to this drawback, their application is limited. This issue is important for the development of health monitoring techniques because the user of such methods needs to have confidence
that the damage will be recognized while the structure still has sufficient integrity to allow repair.

5. Accuracy in damage detection is completely dependent upon the accuracy in measurement of modal properties of the structure. It is found that the modal properties are inflicted to fluctuation due to variations in the measurement. This makes very difficult to conclude whether the observed changes are due to damage or due to variations in the measurement. This is the serious issue of sensitivity of vibration based techniques, and need to be explored further. For practical applications of the vibration based techniques on real life structures such as tall buildings, bridges, dams, and underground structures, it is needed to reduce the dependence upon measurable excitation forces. Vibrations produced by existing loading system and ambient environmental can be used for exciting the structure. This issue needs be investigated.

6. Several vibration based techniques/ algorithms to detect the damage and to predict the locations of damage developed and validated in the laboratory. Validation of all existing technique should be done on common structures and should be based on real measurements. Hence, the relative merits of these methods and their success in locating the damage should be compared in a sufficiently objective manner. One attempt was done on the I-40 Bridge by Farrar and Jauregui (1998), who compared five vibration-based damage identification methods applied to the same data sets.
2.6 MAJOR DEVELOPMENTS IN GLOBAL TECHNIQUE DURING RECENT YEARS

(1) Kim and Stuffs (2002) derived a new algorithm using only lower modes of vibration to detect locations and severities of damage in structures. Verification of algorithm was done on the two-span continuous beam, which showed improvement in damage location and severity.

(2) Ren and Roeck (2002) proposed a method to predict the location and severity of damage using changes in frequencies, mode shapes and finite element modelling. The method was validated using simulated data and real measurement data, which yielded satisfactory result.

(3) Rucka and Wilde (2006) proposed a method for estimating the damage location by analyzing the mode shape by using wavelet transform. Gaussian wavelet transform was used for one dimensional problem like beam element and reverse biorthogonal wavelet for two dimensional structures like plate.

(4) Brownjohn (2007) presented the application issues of SHM on the various form of civil infrastructure like dams, tall buildings, bridges, offshore installations, towers, nuclear installations etc. Several case studies based on vibration technique were covered from practical point of view.

(5) Yan et al. (2007) presented detail review of vibration based techniques for damage detection.

(6) Fang et al. (2008) presented a method to measure the stiffness of damaged beam by finite element model updating and bi-dimensional damage function. Proposed method was validated on an RC frame structure.
(7) Guan and Karbhari (2008) addressed some of the weaknesses of the damage detection method based on modal curvature. An improved damage index was proposed, which based on modal curvature and modal rotation. The performance of proposed method was confirmed by numerical simulation and experimental validation.

(8) Sakellariou and Fassois (2008) presented a method for detection and identification of damage based on stochastic functional model. Severity of damage was also estimated using proposed method. The method was validated on scaled aircraft skeleton structure.

(9) Hu and Wu (2009) presented a non destructive method for damage detection using experimental modal analysis data and modal strain energy method. A damage index was defined as the ratio of modal strain energy before and after damage. A small damage was detected in aluminum plate structure using the proposed approach.

(10) Shih et al. (2009) also presented a non destructive method for damage detection using combination of modal flexibility method and modal strain energy method. The proposed method is applicable on both beams and plates and is able to detect the local as well as global multiple damages.

2.7 LOCAL TECHNIQUES

Another category of damage detection methods are the so called ‘local technique’ due to their limited influence range, as opposed to the global techniques. They rely on localized
structural interrogation for detecting damages and response the health of structure. Local techniques can be classified into two categories:

(a) Conventional techniques

(b) Technique using smart materials

2.7.1 Conventional Techniques

Some of the methods in conventional techniques category are the ultrasonic techniques, acoustic emission, eddy currents, impact echo testing, magnetic field analysis, penetrant dye testing, and X-ray analysis, which are discussed here briefly. Technique using smart materials is main concern of this thesis and discussed in detail.

2.7.1.1 Ultrasonic Technique

The ultrasonic techniques are based on elastic wave propagation and reflection within the material for non-destructive strength and characterization. A piezo-electric probe is employed to transmit high frequency waves into the material. These waves reflect back on encountering any crack, whose location is estimated from the time difference between the applied and reflected waves. These techniques exhibit higher damage sensitivity as compared to the global techniques. However, they share few limitations, such as:

(i) They typically employ large transducers and render the structure unavailable for service throughout the length of the test.

(ii) The measurement data is collected in time domain that requires complex processing.

(iii) Since ultrasonic waves cannot be induced at right angles to the surface, they cannot detect transverse surface cracks (Giurgiutiu and Rogers, 1997).
(iv) They do not lend themselves to autonomous use since experienced technicians are required to interpret the data.
(v) Technique is very costly compare to other technique.

2.7.1.2 Acoustic Emission Technique

In acoustic emission technique, elastic waves generated by plastic deformations, moving dislocations and disbands are utilized for analysis and detection of structural defects. It requires stress or chemical activity to generate elastic waves, thereby facilitating continuous surveillance. However, the main problem to damage identification is posed by existence of multiple travel paths from the source to the sensors. Also, contamination by electrical interference and mechanical ambient noise degrades the quality of the emission signals (Park et al., 2000a; Kawiecki, 2001).

2.7.1.3 Eddy Currents Technique

The eddy currents perform a steady state harmonic interrogation of structures for detecting surface cracks. A coil is employed to induce eddy currents in the component. The interrogated component, turn induces a current in the main coil and this induction current undergoes variations on the development of damage, which serves an indication of damage. The key advantage of the technique is that it does not warrant any expensive hardware and is simple to apply. However, a major drawback is that its application is restricted to conductive materials only, since it relies on electric and magnetic fields. A more sophisticated version of the method is magneto-optic imaging, which combines eddy currents with magnetic field and optical technology to capture an image of the defects (Ramuhalli et al., 2002).
2.7.1.4 Impact Echo Technique

In impact echo testing, a stress pulse is introduced into the interrogated component using an impact source. As the wave propagates through the structure, it is reflected by cracks and disbands. The reflected waves are measured and analyzed to yield the location of cracks or disbands. Though the technique is very good for detecting large voids and delimitations, it is insensitive to small sized cracks (Park et al., 2000a).

2.7.1.5 Magnetic field technique

In the magnetic field technique, a liquid containing iron powder is applied on the component to be interrogated, subjected to magnetic field, and then observed under ultra-violet light, which makes the cracks are directly visible. The technique is however restricted to magnetic materials only. Also, the component must be dismounted and inspected inside a special cabin. Hence, the technique is not very suitable for in situ application.

2.7.1.6 Penetrant dye test

In the penetrant dye test, a coloured liquid is brushed on to the surface of the component under inspection, allowed to penetrate into the cracks, and then washed off the surface. A quick drying suspension of chalk is thereafter applied, which acts as a developer and causes colored line to appear along the cracks. The main limitation of this method is that it can only be applied on accessible location of structure since it warrants active human intervention.
2.7.1.7 X-ray technique

In X-ray method, the test structure is exposed to X-rays, which are then re-caught on film, where the cracks are delineated as black lines. Although the technique can detect moderate sized cracks, very small surface cracks (incipient damages) are difficult to be captured. A more recent version of the X-ray technique is computer tomography, whereby a cross-sectional image of solid objects can be obtained. Although originally used for medical diagnosis, the technique is recently finding its use for structural non-destructive evaluation (NDE) also (e.g. Kuzelev et al., 1994). By this method, defects exhibiting different density and/or contrast to the surroundings can be identified.

Table 2.1 summarises the typical damage sensitivities of the local NDE methods described above. A common limitation of the local methods is that usually, probes, fixtures and other equipment need to be physically moved around the test-structure for recording data. Often, this not only prevents autonomous application of the technique, but may also demand the removal of finishes or covers such as false ceilings. Moving the probe everywhere being impractical, these techniques are often applied at much selected probable damage locations (often based on preliminary visual inspection or past experience), which is almost tantamount to knowing the damage location a priori. Generally, they cannot be applied while the component is under service, such as in the case of an aircraft during flight. Computer tomography and X-ray techniques, due to their high equipment cost, are limited to very high performance components only (Boller, 2002).

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Table 2.1 Sensitivities of common local NDE techniques (Bhalla, 2004).

<table>
<thead>
<tr>
<th>Method</th>
<th>Minimum detectable crack length</th>
<th>High probability detectable crack length (&gt;95%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic</td>
<td>2mm</td>
<td>5-6mm</td>
<td>Dependent upon structure geometry and material</td>
</tr>
<tr>
<td>Eddy currents (low-frequency)</td>
<td>2mm</td>
<td>4.5-8mm</td>
<td>Suitable for thickness &lt;12mm only</td>
</tr>
<tr>
<td>Eddy currents (high-frequency)</td>
<td>2mm (surface) 0.5mm (bore holes)</td>
<td>2.5mm (surface) 1.0mm (bore holes)</td>
<td></td>
</tr>
<tr>
<td>X – Ray</td>
<td>4mm</td>
<td>10mm</td>
<td>Dependent upon structure configuration. Better for thickness &gt; 12mm</td>
</tr>
<tr>
<td>Magnetic particle</td>
<td>2mm</td>
<td>4mm surface</td>
<td></td>
</tr>
<tr>
<td>Dye penetrant</td>
<td>2mm</td>
<td>10mm surface</td>
<td></td>
</tr>
</tbody>
</table>

2.7.2 Techniques Based on ‘Smart Materials and Smart System’

Smart materials are those materials which have the ability to change their physical properties such as the shape, stiffness, viscosity, etc. in a specific manner under specific stimulus input. Smart materials are one of the components of smart structures. The piezoelectric materials and optical fibers are examples of smart material. Smart structures have ability to sense change in their environment, optimally adjust themselves, and take appropriate action.

According to Ahmad (1988), a system is termed as ‘smart’ if it is capable of recognizing an external stimulus and responding to it with in a given time in predetermined manner. In addition, it is supposed to have the capability of identifying its status and may
optimally adapt its function to external stimuli or give appropriate signal to the user. Smart structures can monitor their own condition, detect impending failure, control, or heal damage and adapt to changing environment. A smart system typically comprises of the following components:

Sensors:
A smart system must gather information about its surroundings before taking the appropriate action. This work is done by sensors. Sensors recognize and measure the intensity of the stimulus (stress or strain) or its effect on the structure. They gather the information about the happenings of the surrounding and finally transfer information to the actuators for appropriate action. There are several smart sensors like optical fiber sensors, piezo film and pizoceramic patches.

Actuators:
A smart system may additionally have embedded or bonded actuators, which respond to stimulus in predetermined manner.

Control Mechanism:
A smart structure must have a mechanism from intersection of sensor and actuator. Both sensors and actuators integrated in feedback architecture for the purpose of controlling the system states.

2.8 PIEZOELECTRICITY
The piezoelectric effect was discovered in 1880 by Jacques and Pierre Curie. It occurs in certain crystalline minerals, which when subjected to a mechanical force, become
electrically polarized. Tension and compression generates voltages of opposite polarity and in proportion to the applied force. This is called the direct effect. The converse effect was discovered by Lippman in 1881 in which the crystal was exposed to an electric field, under which it lengthened or shortened according to the polarity of the electric field and in proportion to the strength of the field. These behaviours are called the direct piezoelectric effect and the converse piezoelectric effect, respectively. A smart system must have a mechanism for integrating the sensors and actuators. Piezoelectric materials are smart materials because they generate a surface charge in response to applied mechanical stress. Conversely, they undergo a material deformation in response to an applied electric field. This unique capability enables the material to be used as a sensor and an actuator.

In the 20th century, metal oxide-based piezoelectric ceramics and other manmade materials enabled engineers to employ the direct and converse piezoelectric effects in several new applications. These materials are generally physically strong and chemically inert, and they are relatively inexpensive to manufacture. The composition, shape and dimensions of a piezoelectric ceramic element can be tailored to meet the requirement of a specific purpose. Ceramics manufactured from formulation of lead zirconate/lead titanate exhibit greater sensitivity and higher operating temperatures, relative to the ceramics of other compositions. “PZT” material (lead zirconate titanate), is currently the most widely used piezoelectric ceramics.
2.8.1 Applications

Since this thesis is primarily concerned with piezoelectric materials, some typical applications of these materials are briefly described here. Traditionally, piezoelectric materials have been well-known for their use in accelerometers, strain sensors (Sirohi and Chopra, 2000b), emitters and receptors of stress waves (Giurgiutiu et al., 2000b; Boller, 2002), distributed vibration sensors (Choi and Chang, 1996; Kawiecki, 1998), actuators (Sirohi and Chopra, 2000a) and pressure transducers (Zhu, 2003). However, since the last decade, the piezoelectric materials, their derivative devices and structures have been increasingly employed in turbo-machinery actuators, vibration dampers and active vibration control of stationary/moving structures (e.g. helicopter blades, Chopra, 2000). They have been shown to be very promising in active structural control of lab-sized structures and machines (e.g. Manning et al., 2000; Song et al., 2002). Structural control of large structures has also been attempted (e.g. Kamada et al., 1997). Other new applications include underwater acoustic absorption, robotics, precision positioning and smart skins for submarines (Kumar, 1991). Skin-like tactile sensors utilizing piezoelectric effect for sensing temperatures and pressures have been reported (Rogers, 1990). Very recently, the piezoelectric materials have been employed to produce micro and nano scale systems and wireless inter digital transducers (IDT) using advanced embedded system technologies, which are set to find numerous applications in micro-electronics, biomedical and SHM (Varadan, 2002; Lynch et al., 2003b). Recent research is also exploring the development of versatile piezo-fibres, which can be integrated with composite structures for actuation and SHM (Boller, 2002).
The most striking application of the piezoelectric materials in SHM has been in the form of EMI technique. Applications of the piezoelectric materials in global dynamic techniques are explored in this thesis. In brief, piezoceramic patches namely PZT wafers have substantial applications as sensors, actuators, electric generators and ultrasonic transducers.

2.9 PROBLEMS IN APPLICATION OF PIEZOELECTRIC MATERIAL FOR STRUCTURAL HEALTH MONITORING

Piezoelectric ceramic elements are used to monitor the health of structures via the EMI technique since mid nineties. Damage detection is based on comparison of signature with benchmark signature. Ideally, the change in signature should be due to deterioration of health of structure only, not from any other reason. However, it is possible that signature of PZT can change due to other reasons such as:

2.9.1 Aging

PZT patches erode gradually, in a logarithmic relationship with time after polarization (PI Ceramic, 2009). Exact rates of aging depend on the composition of the ceramic element and the manufacturing process used to prepare it. It may possibly induce that change in the benchmark signature.

2.9.2 Electrical Limitations

PZT patches depolarize if it is exposed to a strong electric field of polarity opposite that of the polarizing field. The field of 200-500 V/mm or greater typically have a significant depolarizing effect. The degree of depolarization depends on the grade of material, the exposure time, the temperature, and other factors. An alternating current will have a
depolarizing effect during each half cycle during which polarity is opposite that of the polarizing field.

2.9.3 Mechanical Limitations
Application of mechanical stress on piezoelectric material beyond certain limit can destroy the alignment of dipole. This limit depends upon the type of grade and the brand of the material used to prepare the PZT patches.

2.9.4 Thermal Limitations and Temperature Fluctuations
If a piezoelectric ceramic material is heated to above the Curie temperature, the domains become disordered and the material gets depolarized. The recommended upper operating temperature for a ceramic usually is approximately half-way between 0°C and the Curie point. Within the recommended operating temperature range, temperature-associated changes in the orientation of the domains are reversible. On the other hand, these changes can create charge displacements and electric fields. Also, sudden temperature fluctuations can generate relatively high voltages, capable of depolarizing the ceramic element. A capacitor can be incorporated into the system to accept the superfluous electrical energy. In general, temperature fluctuations affect the properties such as $d_{31}, \varepsilon_{33}$, and $Y^E$ of the PZT patch, and to some extent structural properties of the host system. Hence, temperature fluctuations also lead to horizontal/vertical shift in the signature.

2.10 GEOMETRIC DETAILS OF PZT PATCHES
There are several types of PZT patches commercially available in market in different geometries (circular, rectangular and square) as well as varying thickness. Electrodes
position varies from patch to patch. Electrodes are situated on opposite side in some PZT patches whereas in others the electrode from the bottom edge is wrapped around the thickness, so that both electrodes are available on one side of the PZT patch, facilitating when the other side to be bonded to the host structure. In EMI technique, PZT patches of sizes ranging from 5 mm to 15 mm and thickness from 0.1 to 0.3 are best suited for most structural materials such as steel and RC. Such thin patches usually have thickness resonance frequency of the order of few MHz (Bhalla, 2004). A typical PZT patch manufactured by PI Ceramic (2009) is shown Fig. 2.1.

![Fig. 2.1 Detail of PZT patch](image)

### 2.11 ELECTRO MECHANICAL IMPEDANCE (EMI) TECHNIQUE

The EMI technique is a relatively new technique for SHM. The technique was first invented by Liang et al (1994) and then implored upon by Giurgiutiu and coworkers (1997, 2000, 2002); Park (2000) and Bhalla (2004). In this technique, basically a PZT patch is surface bonded or embedded inside the structures to the monitored, as shown in Fig. 2.2. The patch is assumed to be infinitesimally small and possessing negligible mass and stiffness as compared to the host structure. When an alternating electric field is applied to the patch, it expands and contracts dynamically in direction ‘1’. Hence, two end points of the patch can be assumed to encounter equal impedance $Z$ from the host
structure. The patch (length \(2l\), width \(w\) and thickness \(h\)) behaves as thin bar undergoing axial vibration. An electro-mechanical model of the system is shown in Fig. 2.2 (b), where the structure has been replaced by two equal mechanical impedances \(Z\). The complex electro-mechanical admittance \(\overline{Y}\) of the coupled system shown in this figure can be derived as (Liang et. al, 1994; Bhalla, 2004)

\[
\overline{Y} = 2\omega j \frac{wl}{h} \left[ \frac{\varepsilon_{33}^T}{Z_a} + \left( \frac{Z_a}{Z + Z_a} \right) d_{31}^2 \overline{Y} E \left( \frac{\tan \kappa d}{\kappa d} \right) - d_{31}^2 \overline{Y} E \right]
\]

(2.5)

where \(d_{31}\) is the piezoelectric strain coefficient of the PZT material, \(\overline{Y} E\) the complex Young’s modules under constant electric field, \(\varepsilon_{33}^T\) the complex electric permittivity at constant stress, \(Z_a\) the mechanical impedance of the PZT patch, \(\omega\) the angular frequency and \(\kappa\) the wave number.

The electro-mechanical coupling represented by Eq. 2.5 is utilized in damage detection in EMI technique. The mechanical impedance \(Z\) of the host structure is the function of the
structural parameters, i.e., as stiffness, the damping and the mass. Any damage to the 
structure will cause these parameters to change, and hence changes the drive point 
mechanical impedance $Z$. Consequently, the electro-mechanical admittance $\tilde{Y}$ will 
undergo change, and this serves an indicator of the state of health of the structure. Due to 
high frequency of excitation, the EMI has very high sensitivity to damage, typically of 
the order of the ultrasonic techniques described earlier (Park et al. 2003). Typically, the 
technique can detect flexural and shear crack before they could be visible to the naked 
eyes (Bhalla and Soh, 2004a).

2.12 METHOD OF APPLICATION
In the EMI technique, a PZT patch is bonded to the surface of structure using high 
strength epoxy adhesive or embedded in structure whose health is to be monitored. The 
signature of the PZT patch is acquired over a high frequency range (30-400kHz), by 
means of LCR meter or impedance analyzer. The signature is complex in nature, 
consisting of the real and the imaginary component called conductance and susceptance 
respectively. The LCR meter imposes an alternating voltage signal of 1 volts root mean 
square to the PZT patch over the user specific preset frequency range. Higher voltage 
imposed to the PZT patch has no influence on the conductance signature, but might only 
be helpful in amplifying weak structural nodes (Sun et al., 1995). The signature in the 
healthy condition forms the benchmark signature. In future time, when it desired to 
assess the health of structure, the signature is acquired again and compared from 
benchmark signature. Any deviations in signature from benchmark signature indicate the 
crack/damage in structure.
2.13 SELECTION OF FREQUENCY RANGE

Basic drawback of global dynamic techniques is low sensitivity in detecting hairline cracks and incipient damage because of the high wavelength stress. Sensitivity of any technique depends upon detection of hair crack/incipient damage. In the EMI technique, the excitation frequency is typically in kHz range so that the wavelength of the resulting stress wave is smaller than the typical size of the defect to be detected (Giurgiutiu and Rogers, 1997). The EMI technique acts best a frequency range from 30 kHz to 400 kHz for PZT patches 5 to 15mm in size (Park et al., 2003b). As the frequency increases, the sensing radius decreases. Frequencies greater than 200 kHz are favorable in localizing the sensing range. However, frequencies greater than 500 kHz are found unfavorable because the sensing region of the PZT patch becomes too small and the PZT signature shows adverse sensitivity to its own bonding condition rather than any damage to the monitored structure.

On the other hand, lower frequency range cover larger sensing region, which affect the sensitivity of technique. Giurgiutiu and Zagrai (2002) reported that piezo-impedance transducers do not behave well frequencies less than 5 kHz and technique loses its utility completely below 1 kHz.

2.14 SENSING ZONE OF PIEZO-IMPEDANCE TRANSDUCERS

Sensing zone of PZT patches depends upon the propagation of stress waves. Denser or non-homogeneous the medium like concrete, lesser the sensing region. Hence, the PZT patches have limited sensing zone based on properties of material and operating frequency. Park et al. (2000a) reported that the sensing radius of a typical PZT patch
might vary anywhere from 0.4m on composite reinforced structures to about 2m on simple metal beams.

2.15 ADVANTAGES OF EMI TECHNIQUE

There are several advantages of EMI techniques which are summarized below

1. Basic feature of EMI technique is higher sensitiveness to incipient damage. The sensitivity of the EMI technique is in order of ultrasonic techniques. (Park et al., 2003a). This technique is applicable to every type of structure and each component of structure like tall buildings, tunnels, curved faced structures and foundation due to small size of PZT patches.

2. This technique is immune from mechanical, electrical, electromechanically noise due to high frequency range functionality. Due to this reason, its sensitivity is high.

3. Since the same PZT patches act as actuator and sensor, this save the number of transducers and the associated wiring.

4. EMI technique is very cost effective due to low cost of PZT patches. Typical cost of one PZT patches lie between US $1 to US $10.

5. Since only PZT patch signatures are required to evaluate the health of structure, hence, online monitoring of structures is possible using this technique. Quick observation about the health of structure is possible using this technique, because extracted data from PZT patch does not require any type of transformation or complex processing.

6. There is no bound of time in the application of this technique. Technique can be applied any time in service life of structure. However, it assesses the health after the
installation time. It can not extract the earlier history of structure. It uses the present information as benchmark to predict the health in future.

7. There is no requirement of any type of modelling to monitor the health of structure. It saves the time in calculation and use of any type of software. Hence technique is very suitable for complex structure.

8. Due to negligible mass of PZT patches, its stiffness is several orders below that of the monitored structures. Hence, application of this technique does not change the dynamic or the static behaviour of the monitored structure.

9. Hardware used to measure the signature of PZT patches is very simple and portable and easily available commercially. Hence, it makes the technique cost effective.

2.16 LIMITATIONS OF EMI TECHNIQUE

1. To apply this technique, a preplan is required. For example, it is impossible to implement this technique to detect the damage in foundation after constructions, since the PZT patches can not be installed after construction.

2. PZT patches are very brittle, only sound technical personnel can install. Special attention is required to monitor these PZT sensors for deteriorations / breaking. Once PZT patches installed, it cannot be reused.

3. PZT sensor has limited sensing zone, ranging from 0.4m to 2m only, depending upon the material and geometrical configuration.

4. Due to limited sensing zone, large number of PZT patches will be required to complete monitoring of civil structure such as bridge, tall buildings and dams. One PZT patch contain two wires, hence there will be wiring problem.
2.19 MAJOR DEVELOPMENTS DURING RECENT YEARS

Bhalla (2004) has provided a comprehensive review of the developments in EMI technique since its invention in 1995. Few major developments are reproduced below for the sake of completeness.

(1) Application of the EMI technique for SHM on a lab sized truss structure was first reported by Sun et al. (1995). This study was then extended to a large-scale prototype truss joint by Ayres et al. (1998).

(2) Lopes et al. (1999) trained neural networks using statistical damage quantifiers successfully and quantified the damages inflicted on the test structure.

(3) Park et al. (2000a) reported significant proof-of-concept applications of the EMI technique on several civil-structural components. The technique was shown to be very tolerant to mechanical noise also to small temperature fluctuations. Park (2000a) extended the EMI technique to high temperature applications (typically>500°C). Besides, he also developed practical statistical cross-correlation based methodology for temperature compensation.

(4) Soh et al. (2000) established the damage detection and localization ability of piezo-impedance transducers on real-life RC structures by successfully monitoring a 5m span RC bridge during its destructive load testing. In addition, criteria were outlined for transducer positioning, damage localization and transducer validation.

(5) Park et al. (2000b) were the first to integrate the EMI technique with wave propagation modelling for thin beams (1D structure) under ‘free-free’ boundary conditions, by utilizing axial modes.
After the year 2000, numerous papers appeared in the literature demonstrating successful extension of the technique on sophisticated structural component such as restrengthened concrete members (Saffi and Sayyah, 2001) and jet engine components under high temperature conditions (Winston et al., 2001).

Inman et al. (2001) proposed a novel technique to utilize a single PZT patch for health monitoring as well as for vibration control.

Abe et al. (2002) developed a new stress monitoring technique for thin structural element (such as strings, bags and plates) by applying wave propagation theory to the EMI measurement data in the moderate frequency range (1-10kHz). This has paved the way for the application of the technique for the load monitoring, in addition to damage detection. The major advantage is that owing to localized wave propagation, the technique is insensitive to boundary conditions. However, the suitable frequency band for this application is very narrow, and generally difficult to identify. Also, the method is prone to large errors, especially in 2D component, due to imprecise modeling of the interfacial layer.

Giurgiutiu et al. (2002) combined the EMI technique with wave propagation approach for crack detection in aircraft components. While the EMI technique was employed for near field damage detection, the guided ultrasonic wave propagation technique was employed for far field damage detection.

Peairs et al. (2003) developed a novel low-cost and portable version of impedance analyzer, the major hardware used in the EMI technique, paving way for significant cost-reduction.
(11) Bhalla and Soh (2003) extended the application of EMI technique by developing a new approach. The newly developed approach utilizes both the real and the imaginary component of the admittance signature for damage quantification. Damage detection is based on the extracted structural impedance rather than raw conductance signature.

(12) Naidu and Soh (2004) developed a new approach to detect the location and severity of damage. The EMI technique was integrated with finite element model using higher mode shape.

(13) Soh and Bhalla (2004) successfully developed a new approach for the non-destructive evaluation of concrete using EMI technique. Strength prediction during curing and damage assessment can be done by using the equivalent spring stiffness detected by the PZT patch.

(14) Bhalla and Soh (2004a) introduced a new PZT-structure electro elastic interaction model based on the concept of “effective impedance”. The proposed model can be employed to extract the mechanical impedance of any unknown structure. They successfully validated the model on lab-sized aerospace structural component and a prototype reinforced concrete bridge during a destructive load test. A new fuzzy based damage model was formulated for plain concrete.

(15) Bhalla et al. (2005) extended the application of EMI technique in monitoring underground structures.

(16) Lin et al. (2005) proposed a new technique of SHM called Hilbert–Huang transform (HHT) and compared the results of this technique. However, HHT is only applicable for linear structure.
(17) Ling et al. (2005) developed a transducer by coating the PZT film on the surface of cantilever beam. A PZT coated cantilever was utilized as a transducer for simultaneous sensing and actuating was investigated in view of its potential applications in dynamic measurement of micro scale systems.

(18) Park et al. (2006) performed experimental studies on steel bridge components by using EMI technique and lambwave method for damage detection. The root mean square deviations (RMSD) in the EMI technique and wavelet coefficient of lambwaves were found to be good indicator of damage.

(19) Lim et al. (2006) introduced the concept of self-sensing piezo-impedance transducers which is helpful for automated structural health monitoring. This method was found to be able to successfully perform structural identification and damage diagnosis.

(20) Hey et al. (2006) presented treatment of practical issues concerning the implementation of the EMI technique for SHM using PZT transducers. They studied the effect of environment on the admittance signature of PZT and proposed simple and economic coating to protect the PZT patches.

(21) Su et al. (2006) proposed the embedded sensor network technique for improving the overall integrity of functionalized composite structures engaged in aircraft. An excellent identification capability was observed during experimental study.

(22) Cheng et al. (2007) presented the analysis of shear mode PZT actuator for deflection and performed the experiment on beam shaped structure. The analytical solution showed good agreement with experimental value.
Yang et al. (2007) extended the application of the EMI technique for comprehensive monitoring of rocks. A detailed experimental study was conducted on rock specimens. It was observed that piezo-impedance transducers could detect crack even before they reached macroscopic dimension.

Yang et al. (2008) presented the real life application of the EMI technique. The effect of temperature and bonding thickness on admittance signature of PZT patch were studied experimentally as well as numerically. It was found that thick bonding thickness and high frequency excitation to PZT patch were undesirable at high temperature.

Ihn and Chang (2008) presented a damage detection method using piezoelectric sensor and actuator without any modelling. Location and severity of damage can be predicted using proposed method in metallic and composite structure. Proposed method was verified on Airbus fuselage panels.

Park et al. (2009) proposed modified electromechanical impedance model. Quality assessment of a PZT and coupling degradation effects between a PZT and bonding layer were incorporated into the traditional electromechanical impedance model for better estimation of the electromechanical impedance signatures.

Bhalla et al. (2009) proposed new low-cost hardware set-ups as viable substitutes for conventionally employed cost-intensive impedance analyzers/ LCR meters for implementation of the EMI. Hence, EMI technique can be proved more economical compared to other existing non-destructive technique.
2.20 NEEDS FOR FURTHER RESEARCH IN EMI TECHNIQUE

(i) In spite of key advantages over other NDE technologies that should be based on status at present, the difficulties in developing a theoretical model at high frequencies renders the EMI technique unable to correlate the changes in signature with specific changes in structural properties (Lopes et al., 1999). Hence, no comparison can be found in the literature between theoretical and experimental electrical admittance spectra, especially in 100-200 kHz frequency range. Giurgiutiu et al. (2000) acknowledged that the main barrier to the widespread industrial application of the EMI technique is the meager understanding of the multi-domain interaction between the PZT patch and the host structure. The wave propagation dynamics associated with vibrating PZT patches has also not been thoroughly investigated so far.

(ii) The sensing region of the PZT patch varies from material to material. The parameters which are responsible for this variation should be studied and a relation should be developed with material physical properties.

(iii) The changes in signature of PZT patch due to ageing should be studies and a relation should be developed between signature deterioration and time.

(iv) Equivalent parameters have been extracted from using real and imaginary part of PZT patch signature (Bhalla and Soh, 2004). These parameters are frequency dependant and no relation with physical properties of structures. A relation should be developed between physical properties like stiffness, damping etc and equivalent parameters.
(v) The incipient to moderate damage can be located between two PZT patches sensor using EMI technique. However, no algorithm is available to locate the damage exactly; a rational algorithm should be developed for this.

(vi) For practical application of the technique, it is very important to address the issues of sensor calibration, validation and self-diagnostics.

### 2.19 Hardware/ Technology Considerations

(i) PZT patches are surfaces bonded using good quality adhesive and can not be used again. A technology should be developed so that it can be reused like accelerometer.

(ii) Bonding process of PZT patch on the surface of structure or embedding the PZT should be standardized for uniform bonding layer of adhesive epoxy.

(iii) Presently, the commercial LCR meter is used in the EMI technique are very expensive (> US$26000) and bulky. Besides, the requirements of wiring could seriously limit the practical application of the technique on real-life structures. Although Peairs et al. (2003) developed a novel low-cost and portable impedance analyzer, the data acquisition, processing and signal transmission are still elementary.

(iv) Park et al. (2003b) suggested the integration of local computing units with sensor systems so as to save energy consumption in data transmission to any central processing unit. Utilizing ambient vibrations for deriving necessary operational power can also be of great practical advantage since this would eliminate the requirement of replacing batteries periodically in wireless applications.
(v) Many practical aspects such as protection of PZT patches against harsh environmental conditions for long serviceability and the reliability of the adhesive bonding under extreme conditions need to be investigated.

2.20 INTEGRATED APPROACH

There are several global and local techniques of SHM, each with advantages and drawbacks. For example, local techniques are able to capture local damage but it is difficult to apply upon the whole structure practically. Basic problem is that no single technique is able to monitor the health of structure comprehensively. There are requirements of large number sensors to apply a local technique on civil structures like bridges, tall building and dams. It is very difficult to generate the data in routine way. The technique is uncertain about damage/crack when it occurs in the structure. In these scenarios, practically it is impossible to gather response and analyze the data daily using local techniques. For example, if the local technique, ultrasonic method is used for damage detection of a bridge structure, it takes several days for completing. On the other hand global techniques are less sensitive for incipient damage. EMI technique is the most sensitive amongst local technique but it also acts locally. Also, there is one major difficulty, if traditional local and global techniques are applied on a structure; separate sensors are used in each technique. It will increase the cost and also lead the problem of wiring.

Due to these problems, it is decided to integrate a local technique with global technique. There are several combinations of integration, but new integrated technique should be
sensitive, cost effective as well as easy in application. Considering these criteria, integration of EMI technique with global dynamic technique will provide the best solution. Also, it is decided to develop a sensor system, which is compatible with both the techniques. Traditional techniques use very expensive sensors and instrument in their application. ANN is also used to facilitate integration especially for damage localization and severity assessment. A brief description of ANN is provided in the next section.

2.21 ARTIFICIAL NEURAL NETWORK

ANN is a mathematical model composed of a large number of processing elements organized into layers. All processing elements are interconnected and process several inputs simultaneously, reinforce some, and diminishing others to produce the desired output. The neural networks are particularly useful for modelling a non linear system with a number of variables. ANN has received increasing attention for use in detecting damage in structures based on modal parameters.

2.21.1 Basic unit of ANN

Inputs are the signals to the processing element just as the input (stimulation levels) to a neuron. All the input signals come to the processing element simultaneously. In response, the processing element responds depending on some threshold level. The weighting factors of connection act like a filter in the form of multiplicative coefficient of the output sent from one processor to another, and may serve to increase or decrease the activation of the receiving processor. In artificial neuron, generally, two transfer functions: input function and activation function operate over the inputs \( I_1, I_2, \ldots, I_n \). The input signals
are first processed by the input function (generally the summation function) and the results $\text{net}_j(t)$ are then activated by an activation function and/or output, which produces the output signal. The learning mechanisms for imparting learning or self-organization to the multilayer networks are classified as supervised learning and unsupervised learning (Wasserman, 1989). Training consists of presenting input and output data to the network. This data are referred as training set (or training patterns). The training phase is considered complete when the neural network produces the desired outputs for a given sequence of inputs. There are various learning rules, but only the delta rule, which is most commonly used, is briefly discussed here. The delta rule is based on continuously modifying the strength of the connections to reduce the difference (the delta), or the error, between the desired output value and the current output value of a processing element. The rule is also referred as a least mean square learning rule, because it minimizes the mean squared error (MSE). In civil engineering problem, generally feed forward-back propagation neural networks are used. A brief discussion about this network is given in next subsection.

2.21.2 The Back-Propagation Neural Networks

A back propagation neural network is often constructed from three or more layers as shown in Fig. 2.3; one input layer, one output layer and one or more hidden layers.

The first phase of operation of the feed forward-back propagation neural network is called “feed forward”. During this operations, for the given input vector $I(t)$, for $t^{th}$ training pattern, the output $H_n(t)$ of a neuron in the hidden layer is
\[ H_n(t) = f[Nets(t)] \] (2.6)

where,

\[ Nets(t) = \sum W_{hi}(t) \cdot I_i(t) \] (2.7)

\( f(x) = \) a differentiable activation function

**Fig. 2.3** A typical three layer back propagation neural network
Similarly, the output of the unit $O$ in the output layer, $O_o(t)$ is

$$O_o(t) = f[Net_o(t)] \quad (2.8)$$

Where,

$$Net_o(t) = \sum W_{oh} \cdot f[\sum W_{hi}(t) \cdot I_i(t)] \quad (2.9)$$

The second phase of operation of the back propagation neural network is called the “error back propagation”. The error function, $E(o)$ is defined by the sum of squares of the difference between the desired output, $T_o(t)$ and the network output $O_o(t)$, as follows:

$$E(O) = \frac{1}{2} \sum [T_o(t) - O_o(t)]^2 \quad (2.10)$$

where, the summation extended over the number of training patterns. For the hidden layer to output layer connections, the adaptive rule of the weight $W_{ch}$ can be determined by generalized delta rule

$$W_{ch}(t + \Delta) = W_{ch}(t) + \Delta W_{ch} \quad (2.11)$$

where,

$$\Delta W_{ch} = -\eta \frac{\partial E(O)}{\partial W_{ch}} = -\eta \sum \Delta_o(t) \cdot H_h(t) \quad (2.12)$$

and $\Delta_o(t)$ is given by,

$$\Delta_o(t) = \frac{d(Net_o)}{dNet_o}[T_o(t) - O_o(t)] \quad (2.13)$$
Where, $\eta$ the coefficient and $h$ is is called the learning rate. Similarly, the adaptive rule for the input layer to hidden layer connections, $W_{hi}$ can be written as follows:

$$\Delta W_{hi} = -\eta \frac{\partial E(o)}{\partial W_{hi}} = -\eta \sum_h \Delta_h(t)I_i(t) \quad (2.14)$$

$$\Delta_h(t) = \frac{df(Net_h)}{dNet_h} \sum_o W_{ho} \Delta_o(t) \quad (2.15)$$

Applying the differentiation process successively, the error back propagation rules can be extended to the networks with any number of hidden layers. Their weights will be continuously adjusted until the outputs to reach to a desired accuracy. The accuracy of the trained network depends upon number of hidden layers, number of neurons in a hidden layer and number, distribution and format of training patterns (Flood and Kartam, 1994).

### 2.22 Advantages of Neural network

There are several advantages of ANN over conventional procedure which are described below.

a. ANN is particularly used when the relationship between the dependant and the independent variables is poorly established and also some dependant variables are unknown.

b. ANN produces meaningful solution of a problem even when the input data contains error or is incomplete. It abstracts essential characteristics from input and filters irrelevant data.
c. ANN adopts solutions overtime to compensate for changing circumstances. It has ability to update results when new data are added in the input library. It means currently developed ANN can be used in future also.

d. ANN can tackle linear as well as non-linear problems. It does not require a priori information concerning phenomenological nature of the structure (Masri et al. 2000).

e. ANN has ability to extract generalized solutions to a problem from a set of examples. This enables its use for problems other than the training set.

2.23 Limitations of neural network

There are several limitations of ANN, which are described as follows;

1. ANN always produces approximate results. They cannot be used where exact results are required. The accuracy depends upon training process. If the network is not properly trained, it produces wrong results.

2. There is a requirement of lot of data to train the network. A lot of time and resources might be required to generate the data.

3. A trained ANN can be used only on the same type of problem for which data are trained.

4. Several trials are required to train the network with different number of hidden layers and number of neuron till appropriate configuration of the network is arrived.

5. For data not in the training set and where no explicit relation exists between input and output, it is not possible to access that the results produced by ANN are wrong or right.
Some recent developments in this area include;

1. Rogers (1994) presented the application of ANN for structural design. Few guidelines were suggested to select the training pairs and determining the number of nodes on the hidden layers so that ANN can reduce the amount of time to optimize the design process.

2. Mukherjee and Deshpande (1995) used the ANN with rule based expert system (RBES) approach to structural design programming. This novel approach removed the lack in learning capabilities and requires the rule to be stated explicitly.

3. Kao and Hung (2003) presented damage detections method in structures in two steps. The first step, system identification, used neural system identification networks (NSINs) to identify the undamaged and damaged states of a structural system. The second step, structural damage detection, used the aforementioned trained NSINs to generate free vibration responses with the same initial condition or impulsive force.

4. Sahin and Shenoi (2003) combined the curvature mode shape method, frequencies change method with ANN to identify the location and severity of damage in beam like structure. The proposed ANN was trained with the vibration data generated by strain gauge and accelerometer which were used to obtain the model parameter and natural frequencies of the beam structure.

5. Xu et al. (2004) proposed the method for identification of stiffness and damping coefficient without eigen value analysis and extraction and optimization process using back propagation ANN. They used only time domain response of structure.
The result was satisfactory even in the presence of noise. The proposed method was validated on the five storey building.

6. Lee et al. (2005) presented a method to detect the presence, location and severity of damage in bridge structures with the help of ANN. The input data was derived from model properties of the bridges. The result was validated on multi-girder bridge.

7. Kesavan et al. (2006) presented the method to detect the presence, location and severity of damage in T-joint composite structures with the help of ANN. Data was derived from strain gauges which were installed on the joints.

8. Bakhary et al. (2007) investigated the damage detection method using ANN. They proposed statistical approach to take into account the effect of uncertainties in developing an ANN model. The developed approach was applied to detect simulated damage in a numerical steel portal frame model and also in a laboratory tested concrete slab.

9. Efstathiades et al. (2007) proposed a method to identify possible imperfections in a typical curtain-wall system. The database was developed from the results of the parametric finite element analysis of the models, concerning different fault positions. Presence and location of damages were predicted using proposed method in curtain-wall system.

10. Ahadzadeh et al. (2008) developed an algorithm to predict about the damaged buildings after earth quake using ANN with co-occurrence matrix. Using presented algorithm, sixty percent damaged buildings were detected after earth quake.
11. Mehrjoo et al. (2008) presented the method of estimating the damage of joints for truss bridge structures using a back-propagation based neural network. The natural frequencies and mode shapes were used as input parameters to the neural network for damage identification. Numerical examples on truss bridges were presented to demonstrate the accuracy and efficiency of the proposed network.

12. Nui and Ye (2009) presented the algorithm of damage detection in structures using traditional neural network (TNN). The training patterns were generated using a standard FEM program. In the proposed TNN, back propagation learning was employed with two hidden layers. The proposed method was validated on the bridge structure.

2.24 CONCLUDING REMARKS:

This chapter has covered a detailed review of the global SHM techniques, local NDE techniques, EMI technique and ANN. Pros and cons of all techniques were described. In existing techniques, global dynamic technique is best among the global techniques and the EMI technique is best among the local techniques. It is also realized that integration approach will be best tool for SHM because it is impossible to monitor the complete health of structure using single technique. Next chapter will cover the sensor systems for SHM.
CHAPTER -3

SENSOR SYSTEMS FOR SHM

3.1 INTRODUCTION

In all SHM techniques, whether global or local, choice of sensors is very crucial. This is because the cost of monitoring system as well as the sensitivity, reliability and utility of the measured data depends on the type of sensors employed. There are numerous sensors available in the market, such as electrical strain gauges (ESG), PZT patches, accelerometers, optical fibre bragg grating (FBG) based sensors and many others. In general, civil engineers have lack of acquaintance with the principle as well as working knowledge of sensors, especially the new generation smart sensors such as the PZT and the FBG sensors.

This chapter covers a brief description of three major sensor types: ESGs, PZT patches and accelerometers. It reports a comparative study of these three sensors applied on laboratory structures: two steel I beams of 2m and 4m lengths.

3.2 SENSOR SYSTEMS FOR STRUCTURAL MONITORING

In this study, three types of sensors were evaluated on beam structures i.e. the ESGs, the PZT patches and the accelerometers. Strain gauges are the most widely used sensors for structural behavior monitoring. On a structural surface, strains are caused by member deformations resulting from bending, torsion, shearing and elongation/contraction. Hence, strain measurements can capture an element’s behavior quite well (Sanayei and
An ESG essentially consists of thin metallic foil grids, bonded to a flexible polyimide film, which is bonded to the surface of the monitored. When the component is loaded, its strain is transferred to the grid and the relative change in resistance, $\Delta R/R$ of the foil can be expressed as

$$\frac{\Delta R}{R} = S_g \varepsilon$$  \hspace{1cm} (3.1)

where, $\varepsilon$ is the strain and $S_g$ is the gauge factor of the ESG.

An accelerometer essentially consists of a seismic mass connected to a base (which is attached to the host structure) by means of a spring and a viscous damper. If $\ddot{x}$ denotes the acceleration of the base, $z$ the relative displacement between the host structure and the seismic mass, the acceleration of the host structure is given by

$$\ddot{x} \approx -z \omega_n^2$$ \hspace{1cm} (3.2)

where, $\omega_n$ is the natural frequency of the seismic mass.

Thus, the acceleration of the host system can be determined by measuring the relative displacement, $z$, between the seismic mass and the base. Eq. (3.2) is valid for small frequencies, typically lower than the natural frequency $\omega_n$ of the spring-damper system. In order to ensure the necessary condition $\omega << \omega_n$, the system should have very stiff spring and a small seismic mass so that $\omega_n$ is maximum possible. Most commercial accelerometers employ piezoelectric transducers as displacement sensors, due to their small mass, high stiffness and low damping. Generally, the accelerometers produce a voltage across their terminals proportional to the measured acceleration.
Piezoelectric materials, already introduced in Chapter 2, are commercially available as ceramics, such as PZT. They exhibit two related phenomena, (i) on application of mechanical stress, they undergo the development of surface charges (direct effect), and (ii) on application of electric field, they undergo mechanical strain (converse effect). The following equation describes the direct effect, which is used in sensor applications

\[ D_3 = \varepsilon_{33}^T E_3 + d_{31} T_1 \]  \hspace{1cm} (3.3)

where, \( D_3 \) is the surface charge density, \( E_3 \) the electric field, \( T_1 \) the mechanical stress, \( \varepsilon_{33}^T \) the complex electric permittivity at constant stress and \( d_{31} \) the piezoelectric strain coefficient. Here, the subscript \( 31 \) implies that electric field is applied along direction 3 and strain is measured along direction 1, as shown in Fig. 3.1. In the absence of electric field, \( E_3 = 0 \). Further,

\[ T_1 = Y^E S_1 \]  \hspace{1cm} (3.4)

![Fig. 3.1 Co-ordinate system for a PZT patch](image-url)
where, $Y^E$ is the complex Young’s modulus of elasticity of the PZT material at constant electric field and $S_1$ the strain of the host structure (and also on the PZT patch). By using the theory of parallel plate capacitors, we can derive

$$D_3 = \frac{\varepsilon_3^{T}V}{h} \quad \text{(3.5)}$$

where, $V$ is the potential difference across the terminals of the PZT patch and $h$ the thickness of the patch. Hence, from equations (3.3) to (3.5), strain $S_1$ is related to voltage $V$ by

$$S_1 = \left( \frac{\varepsilon_3^{T}}{d_{31}hY^E} \right) V = K_p V \quad \text{(3.6)}$$

Thus, the output voltage across the terminals of the PZT patch is proportional to the strain of the host structure. The output voltage can be easily measured by oscilloscopes supported by conditioning circuit (Sirohi and Chopra, 2000b). In this study, Agilent 34411A digital multimeter (Agilent Technologies, 2009) has been used for this purpose.

### 3.3 EXPERIMENTAL EVALUATION OF SENSORS

In this investigative study, two steel I beams, both ISMB 150 of lengths 2m and 4m, were instrumented with ESGs, PZT patches and accelerometers. Fig. 3.2 shows the measurement set up, consisting of the test structure, digital multimeter, a personal computer (PC) and a simple hammer. The structure was excited by striking the hammer
and free vibration response was measured using the Agilent 34411A digital multimeter. The same multimeter recorded measurements from all the three sensors one by one. In the case of ESG, the multimeter measured the resistance with time. Eq. (3.1) was used to convert it into strain. In the case of the accelerometer and the PZT patch, the instantaneous voltage across the terminals was measured in the time domain. In all the measurements, a sampling interval of 1-milli second was set in the multimeter. After each measurement, the data recorded in the multimeter was transferred to the PC via the USB interface. The data was transformed from the time domain to the frequency domain by carrying out fast Fourier transform (FFT) in the MATLAB environment. Fig. 3.3 shows the frequencies obtained by this method from the ESG, the PZT patch and the accelerometer for 4m beam. The frequencies of the beams were also determined analytically (for flexure mode) using the theory of dynamics as (Chopra, et al, 2004)

![Experimental test setup.](image)

**Fig. 3.2** Experimental test setup.
where, $f_n$ denotes the $n^{th}$ natural frequency, $E$ the Young’s modulus of the beam, $I$ the moment of inertia, $\rho$ the density, $A$ the cross-sectional area and $L$ the length between supports. These were determined as 134.65 Hz, 538.63 Hz and 1211.94 Hz for 2m beam and 31.96 Hz, 121.84 Hz and 287.63 Hz for the 4m beam. It can be found that the experimental frequencies agree reasonably well with the analytical frequencies.

From Fig. 3.3, it is observed that the PZT patch identified the first three natural frequencies of the 4m beam as 30 Hz, 128 Hz and 228 Hz respectively (Fig. 3.3a). The accelerometer identified the first three natural frequencies as 51 Hz, 149 Hz and 249 Hz respectively (Fig. 3.3b). The ESG, on the other hand, identified the frequencies as 46 Hz, 146 Hz and 245 Hz respectively (Fig. 3.3c).

### 3.4 COMPARATIVE ASSESSMENT OF SENSORS

It can be observed that all the three sensors have captured the natural frequencies of the experimental structures reasonably well. However, from cost point of view, accelerometers are very expensive as compared to strain gauges and PZT patches. Typically, an accelerometer (1mV/g accuracy), costs around Rs 20,000 ($ 400) to Rs 30,000 ($ 600). However, the ESGs and PZT patches are much cheaper. An ESG typically costs around Rs 100 ($ 2) and PZT patch costs in the range Rs 75 ($ 1.5) to Rs 500 ($ 10), depending upon its electrodes (PZT patches with electrodes wrapped around are more expensive).
Fig. 3.3 Frequency responses of 4m beam (a) PZT patch (b) Accelerometer (c) ESG.
Hence, PZT patches are more cost effective. However, these need to be permanently bonded to the structure, which is acceptable keeping in view that they are very low cost and can withstand loads and can function well under extreme conditions. Among the ESGs and PZT patches, it can be observed from Fig. 3.3 that the signal of the PZT is much better than that of the ESG which is quite prone to noise. This is also evident from time domain response, compared in Fig. 3.4. Same trends were repeated in frequency response which is shown in Fig. 3.5.

3.5 EMBEDDED SENSORS

Performance of the PZT sensors is found better compared to other sensors. Since PZT patches are of very small dimension and made of brittle material, for consistent behaviour, they should be protected from harsh environmental condition and other external disturbance. Hence, embedded PZT patches, which can be installed at the time of construction of structure, were also investigated in this research work. This PZT sensor was fabricated, and embedded in 2 m reinforced concrete (R.C.) beam and the compared performance with surface bonded PZT sensor. To prepare the embedded sensor, the form work of cardboard with dimensions 25 x 25 x 25 mm was first filled with cement mortar to the half depth. After 14 days curing, the PZT patch was bonded on the top of the surface of the cement block using good quality epoxy.

After 48 hours, when found satisfactory, the cardboard was filled to full depth with the cement mortar. After 14 days of curing, the cardboard was removed from cement block and was ready to use in any structure under construction. The performance of sensor was studied on the 2 m R.C. beam structure as described in the next section.
Fig. 3.4 Comparison of time domain response (a) ESG (b) PZT
Fig. 3.5 Comparison of frequency response (a) ESG (b) PZT
3.6 COMPARATIVE STUDY OF SENSORS IN RC BEAM

An RC beam of dimensions (2×0.2×0.15m) was simply supported and instrumented with the embedded PZT patch at 0.6m distance from left support and the surface bonded PZT patch at exactly same distance, tested under hydraulic loading machine. The beam was loaded at single point load as shown in Fig. 3.6. The time history at each PZT patch was recorded for two seconds by hammering and the response was measured using Agilent 34411A digital multimeter at 200 µs sampling interval. The beam was in unloaded condition during each excitation. All the measurements were made automatically through programs running in the VEE PRO environment. The recorded voltage data was transformed from time domain to frequency domain by carrying out FFT in the MATLAB environment. First, the beam was loaded up to 50 kN and then unloaded so that an incipient damage is created in the beam. To increase the damage severity, again the load was increased to 70 kN and withdrawn. Loading and unloading process continued till failure of the beam, with the maximum load increased in each successive cycle to 50 kN, 70 kN, 80 kN and 110 kN (failure). Applying the above procedure, time history and frequency plots were determined at each load condition of both sensors. Time histories of both sensors are shown in Fig. 3.7. It is seen from Fig. 3.7 that the time history recorded by the embedded PZT patch is far more smooth and clear compared to the surface bonded PZT patch. Frequency responses at healthy state are shown in Fig. 3.8.
Applying the same procedure, frequency domain responses at different loadings were obtained to determine the first three natural frequencies at different loads. Frequencies after subjecting to 50 kN, 70kN, 80kN and failure are compared with undamaged frequencies and comparison are listed in Tables 3.1 and 3.2.

It is clear from the table that the percentage change in frequencies at different load of the embedded PZT sensor is higher as compared to the surface bonded PZT sensor. Hence, embedded sensor is more sensitive than surface bonded sensor.
Fig. 3.7 Time history of sensors (a) Embedded PZT sensor (b) Surface bonded PZT sensor
Fig. 3.8 FRF of sensors (a) Embedded PZT sensor (b) Surface bonded PZT sensor
Embedding the PZT sensor helps in protecting it from the environment outside the structure. It is safe against erosion and other mechanical forces. It is also safe from outer environment noise and electrical disturbance.

Table 3.1 Comparison of frequencies recorded by embedded PZT sensor

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Undamaged Freq. (Hz)</th>
<th>At 50 kN</th>
<th>At 70 kN</th>
<th>At 80 kN</th>
<th>110 kN (Failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>freq %change</td>
</tr>
<tr>
<td>f₁</td>
<td>40.5</td>
<td>1.06</td>
<td>39.5</td>
<td>2.5</td>
<td>38.5</td>
</tr>
<tr>
<td>f₂</td>
<td>60.0</td>
<td>0.33</td>
<td>58.9</td>
<td>1.8</td>
<td>58.1</td>
</tr>
<tr>
<td>f₃</td>
<td>111</td>
<td>0.0</td>
<td>110.3</td>
<td>0.6</td>
<td>108.5</td>
</tr>
</tbody>
</table>

Table 3.2 Comparison of frequencies recorded by surface bonded PZT sensor

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Undamaged Freq. (Hz)</th>
<th>At 50 kN</th>
<th>At 70 kN</th>
<th>At 80 kN</th>
<th>110 kN (Failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>freq %change</td>
</tr>
<tr>
<td>f₁</td>
<td>39</td>
<td>0.77</td>
<td>38.3</td>
<td>1.79</td>
<td>37.5</td>
</tr>
<tr>
<td>f₂</td>
<td>59.5</td>
<td>0.33</td>
<td>58.5</td>
<td>1.68</td>
<td>58.0</td>
</tr>
<tr>
<td>f₃</td>
<td>112.5</td>
<td>0.0</td>
<td>112.5</td>
<td>0.44</td>
<td>111.0</td>
</tr>
</tbody>
</table>

3.7 LIMITATIONS OF EMBEDDED PZT SENSORS

Basic drawback of the embedded PZT sensor is that it causes a problem with replaceability. Once it embedded in structure it becomes integral part of structure. There is no way to access to it for repairing. It can not be used at once because it takes a time to fabricate. Embedded sensor can be used in limited type of materials like concrete. It is
very difficult to embed in steel structure. Special attention is required to pouring concrete at the time of installation in structure. Special type of wire is used for embedded PZT sensor and life of wire should be more than the life of structure.

3.8 CONCLUDING REMARKS

The performances of different type of sensor are studied. It is found that PZT sensor is better compared to other existing sensors. It can be embedded at the time of construction in structure and manufacturing the embedded sensor is simple. It can be used to measure the dynamic response of the structures. In the next chapter, surface bonded PZT sensor will be used in global as well as EMI technique.
CHAPTER 4

DETECTION OF INCIPIENT AND SEVERE DAMAGE USING PZT PATCHES

4.1 INTRODUCTION

This Chapter primarily deals with comparing the EMI technique with global vibration technique with the specific aim of comparing their damage sensitivities to various levels of damage, and their possible integration. Presence of incipient damage was detected using EMI technique and global dynamic technique was used to detect the presence of moderate to severe damage. Real time monitoring of a structure implies that the damage should be detected at the moment it appears on the structure. But generally, the damage is detected long time after the loss of considerable stiffness, which is not desirable. There are several sensitive local techniques (eg. impact echo, ultrasonic, X-rays, magnetic field techniques etc) to detect incipient damage but they demand costly hardware and are difficult to implement on large structures. Also, it is not practical to monitor the structure on a daily basis by using this hardware, since they might interrupt the service of the structure. Practical engineers will prefer a technique which requires minimum effort, be easy in use, demands minimum hardware and causes no disturbance in service of the structure. It is not desirable to invest heavily for preliminary investigation when occurrence of damage is not certain. On the other hand, if we monitor structure periodically after long intervals, it is possible that the incipient damage increases and becomes much more severe before next monitoring visit. Hence, it is very important to detect the incipient damage as early as possible so that suitable measure can be taken to
avoid any catastrophe. A practical approach is to check for the incipient damage once a
day using the EMI technique. Incipient damage cannot be easily detected by global
techniques due to very small frequency changes. It is therefore not practical to apply the
global technique at initial stage because it is time consuming. The EMI technique, which
is based upon higher frequency range, has sufficiently high sensitivity for incipient
damage (Bhalla, 2004).

There is a lot of confusion about the performance of global dynamic techniques based on
frequency changes to detect the presence of damage. It is almost well established fact that
it is difficult to detect the incipient damage using global dynamic technique. Several
cases are reported in literature that the changes in frequencies are negligible in case of
incipient damage and small in case of moderate to severe damage. Also, for the presence
of damage of same level, frequency change may be different depending on the type of
damage. Hence, the performance of global dynamic techniques is a matter of confusion.
The frequencies of the structure are the function of stiffness and mass of the structure.
Generally, the change in mass of the structure is negligible after damage. Hence, change
in frequency is function of stiffness change only (for given support condition). The
frequencies of structures are global properties and depend upon the stiffness over the
entire structure and not just one section. For given section of structure, stiffness depends
upon the variation of Young’s modulus over length. For a beam of length \( L \), with varying
Young’s modulus \( Y \) and moment of inertia \( I \), bending stiffness \( K \) can be express as

\[
K = \frac{EI}{L^3} \int_0^L Y \, dx
\]  

(4.1)
where, \( c \) is a constant, depending upon the support condition.

Remaining stiffness of structure is a global property and does not depend on one section only. It may be possible that after damage, Young’s modulus of sections near damage reduces considerably and other sections remain same or change negligibly. In this scenario, changes in frequencies may be less or negligible. For example, if a small hole is drilled (artificial damage) in a 2m steel beam, it results reduction of EI (flexural rigidity) of damaged portion only. Hence, change of overall stiffness may be negligible. If the same beam is tested on loading frame and if it develops crack at the place of drilled hole, change in stiffness will be considerable. Because there is reduction of EI of each section and change will be highest near damage. Further as length of beam increases from 2m to 4m, the relative change in stiffness (EI) further reduces. Hence, for the same level damage, percentage change of frequencies may be different. The models are tested in laboratory after creating artificial damage; change of frequencies may be discernible. However, there may be negligible changes in frequencies of a real structure for the same level damage. Further, type of loading applied to structure in creating the damage is also a major issue. Real structures after earthquake loose Young’s modulus of each section because the application of vibrating force on whole structure. On the other hand, a beam or frame structure tested in lab under concentric load, may show a different change in stiffness. Hence, in these scenarios, a comprehensive experiment needs to be conducted on different type of structures changing these parameters. Therefore, following case
studies on structures of different type, under different loading, different damage style and geometry are covered.

(i) 2m RC beam: one point load case
(ii) 2m RC beam: two point load case
(iii) 4m RC beam: two point load case
(iv) The model of RC bridge
(v) 4m steel beam with artificial damage
(vi) One storey frame model of RC building: one point load case
(vii) One storey frame model of RC building tested on shake table

4.2 CASE STUDY

Case Study I: 2m R.C. Beam with point load

An RC beam of dimension (2×0.2×0.15 m) was simply supported, instrumented with an embedded PZT patch at 0.9 m distance from left support, and tested under hydraulic loading machine. The bearing length was 10 cm beyond each support; hence PZT patch was just at in the middle of the beam and at the maximum stress level. The beam was loaded at single point load. The time history of the PZT patch was recorded for two seconds (after unloading) by hammering and the response measured using Agilent 34411A digital multimeter at 200 µs sampling interval as described in Chapter 3. First, the load was increased to 50 kN and then removed so that incipient damage was induced in the beam. To increase the damage severity, the load was increased to 70 kN and removed. Loading and unloading process were continuing till failure of the beam. Since the beam was loaded at a single point, the section below the load had highest stress level.
Stress levels of other section reduced linearly to zero towards supports. Bending moment diagram at failure stage is shown in Fig. 4.1. At failure stage, severe cracks developed at the section below the load, as is shown in Fig. 4.2. Only sections adjacent to load underwent reduction of $EI$ considerably and the reduction was insignificant at other sections.

![Bending moment diagram of 2m beam at failure stage](image)

**Fig. 4.1** Bending moment diagram of 2m beam at failure stage

Frequency plots were determined at each load condition and first three frequencies were identified. The frequencies changes at different load condition are listed in Table 4.1. It is observed that the change in first frequency when the specimen was subjected to a load 50 kN (approximately half of the failure load) is 1.06 % only, which is negligible. Same trend was found for the second and the third frequencies. Changes in frequencies were significant at the load 80 kN and at the failure stage (very severe damage), where the first frequency changed by 13.6 %. It is concluded that it is difficult to detect the incipient level damage by frequency change. However, moderate to severe damages can be easily detected.
Table 4.1 Comparison of frequencies recorded by embedded PZT sensor for RC beam under single point load

<table>
<thead>
<tr>
<th>S.No</th>
<th>Undamaged Freq (Hz)</th>
<th>At 50 kN</th>
<th>At 70 kN</th>
<th>At 80 kN</th>
<th>114 kN (failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq</td>
<td>%change</td>
<td>Freq</td>
<td>%change</td>
<td>Freq</td>
</tr>
<tr>
<td>f₁</td>
<td>40.5</td>
<td>40.1</td>
<td>1.06</td>
<td>39.5</td>
<td>2.5</td>
</tr>
<tr>
<td>f₂</td>
<td>60.0</td>
<td>59.8</td>
<td>0.33</td>
<td>58.9</td>
<td>1.8</td>
</tr>
<tr>
<td>f₃</td>
<td>111</td>
<td>111</td>
<td>0.0</td>
<td>110.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Fig. 4.2 (a) Crack pattern of R.C. beam under one point load at failure (b) Zoomed view of crack
Case Study II: 2m R.C Beam with Two Point Load

An RC beam, same as case study I with same support condition and instrumentation (embedded PZT patch at 0.9m distance from the left support), was loaded. However, the beam was loaded with two point load system, as shown in Fig. 4.3. Since the beam was loaded at two points, one third span of beam was almost highest stress level. Stress levels of remaining two third spans were reduced linearly and at support point it reached zero. Bending moment diagram at failure is shown in Fig. 4.4. At failure stage, severe cracks were developed within central one third span as shown in Fig. 4.5. It can be seen from Fig. 4.5 that double crack was developed on central portion and distance between cracks was 0.47m. Hence, EI of the central one third span reduced almost uniformly. Thus, there was more reduction of overall stiffness (globally) of the beam as compared to Case study I.
Frequency plots were determined at each load case (in the unloaded condition) and first three frequencies were determined, as listed in Table 4.2.

It is observed that change in first frequency after subjecting the specimen to 50 kN load is 1.5 % only, which is again negligible, but greater than from case study I. At failure stage (very severe damage) the change is 17.5 %, which is also significant and greater than compared to case study 1. This is because a larger segment of the beam is damaged, which results greater change in frequencies. Same trend was found for other frequencies.

Table 4.2 Comparison of frequencies recorded by embedded PZT sensor for RC beam under two point loads

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Undamaged Frequencies (Hz)</th>
<th>At 50 kN</th>
<th>At 70 kN</th>
<th>At 80 kN</th>
<th>123 kN (failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Freq.</td>
<td>%change</td>
<td>Freq.</td>
<td>%change</td>
</tr>
<tr>
<td>f₁</td>
<td>42.5</td>
<td>41.86</td>
<td>1.5</td>
<td>41.43</td>
<td>2.5</td>
</tr>
<tr>
<td>f₂</td>
<td>62.0</td>
<td>61.69</td>
<td>0.50</td>
<td>60.76</td>
<td>2.0</td>
</tr>
<tr>
<td>f₃</td>
<td>110</td>
<td>110</td>
<td>0.0</td>
<td>108.9</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Fig. 4.5 Crack pattern of central part of 2m beam at two point load
Case Study III: 4 m RC Beam with Two Point Load

An RC beam of dimensions $4 \times 0.2 \times 0.15$ m was loaded as shown in Figs. 4.6 and 4.7 similar to case II. Only one sixth span of beam was highest stress level.

Table 4.3 Comparison of frequencies recorded by embedded PZT sensor for 4m beam under two point loads

<table>
<thead>
<tr>
<th>S.No</th>
<th>Undamaged Freq. (Hz)</th>
<th>At 10 kN</th>
<th>At 20 kN</th>
<th>At 30 kN</th>
<th>At 37 kN (failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. (%change)</td>
<td>Freq. (%change)</td>
<td>Freq. (%change)</td>
<td>Freq. (%change)</td>
<td>Freq. (%change)</td>
</tr>
<tr>
<td>F1</td>
<td>9.40</td>
<td>9.30</td>
<td>1.0</td>
<td>9.2</td>
<td>2.0</td>
</tr>
<tr>
<td>F2</td>
<td>32.50</td>
<td>32.34</td>
<td>0.50</td>
<td>32.18</td>
<td>1.0</td>
</tr>
<tr>
<td>F3</td>
<td>77.8</td>
<td>77.80</td>
<td>0.0</td>
<td>77.00</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Fig. 4.6 Experimental setup for 4m beam
The frequency changes at different load conditions are listed in Table 4.3. The beam section was same as case study II, but stress distribution differed from the earlier case. The change in the first frequency at failure stage is only 10.5 %, which is lesser than from case study II. The bending moment diagram at failure stage is shown in Fig. 4.8.

It is seen from first three cases that although the maximum bending moment at failure stage are comparable, the overall effect on the stiffness of the beam was different. Accordingly, the change in global frequencies also differed.

Fig. 4.7 Two point load on 4m beam

Fig. 4.8 Bending moment diagram of 4m beam at two point load
Case Study IV: 2m Model of R.C Bridge

An R.C. model bridge of dimension $2 \times 0.5 \times 0.15$m was tested under condition similar to Case study II. In this case, due to larger width, the stress distribution was less severe. Hence, the reduction in the overall stiffness of the structure after damage was less compared to Case study II.

![Fig. 4.9 Model of R.C. Bridge under two point load](image)

The frequencies changes at different load condition are listed in Table 4.4
Table 4.4 Comparison of frequencies recorded by embedded PZT sensor for Model Bridge under two point loads

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Undamaged Frequencies (Hz)</th>
<th>At 40 kN</th>
<th>At 80 kN</th>
<th>At 120 kN</th>
<th>At 137 (failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Freq.</td>
<td>%change</td>
<td>Freq.</td>
<td>%change</td>
</tr>
<tr>
<td>$f_1$</td>
<td>3.5</td>
<td>3.49</td>
<td>0.3</td>
<td>3.46</td>
<td>1.0</td>
</tr>
<tr>
<td>$f_2$</td>
<td>19.5</td>
<td>19.46</td>
<td>0.2</td>
<td>19.40</td>
<td>0.47</td>
</tr>
<tr>
<td>$f_3$</td>
<td>56.5</td>
<td>56.5</td>
<td>0.0</td>
<td>56.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

It is seen that change in first frequency at failure stage (very severe damage) is only 6.5 %, which is lesser than compared to all other cases. Due to comparable dimensions, distribution of stress was very complex, it is difficult to comment on the variation of EI with span. As expected, the frequency changes were smaller as compared to other cases.

**Case Study V: 2m Steel Beam with Artificial Damage**

A steel beam ISMB 150 of length 2m was instrumented with PZT patch on flange surface at 0.65 m distance from the right support. The beam was simply supported at distance of 10 mm from both ends. An artificial damage was induced in three stages by cutting the flange. A crack of 3 mm was first induced by cutting the flange depth completely in first stage as shown in Fig. 4.10. In the second stage, the depth was increased to one forth depth of web. In third stage, the depth was increased up to the half the depth of the web. Post damage frequencies are compared with the undamaged frequencies and comparison is listed in Table 4.5.
Table 4.5 Comparison of frequencies recorded by surface bonded PZT patch on the 2m steel beam

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Undamaged frequencies (Hz)</th>
<th>At first damage</th>
<th>At second damage</th>
<th>At third damage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Freq.</td>
<td>%change</td>
<td>Freq.</td>
</tr>
<tr>
<td>f₁</td>
<td>149</td>
<td>148.55</td>
<td>1.3</td>
<td>143.00</td>
</tr>
<tr>
<td>f₂</td>
<td>552</td>
<td>550.90</td>
<td>0.2</td>
<td>538.40</td>
</tr>
</tbody>
</table>

It is seen that change in first frequency at third damage stage (very severe damage) is only 7.8 %, which is lesser than compared to Case studies I and II. Since damage was created using saw, fewer sections were affected. Hence, there is less reductions of overall
stiffness of the beam. Since the span of the beam was 2m, frequencies changed considerably. In case of practical structure like girder with larger span, percentage change may be reduced.

**Case Study VI: Model of One Storey Building**

An R.C. frame with column height 0.9 m, beam length 1.28 m and cross sectional dimension of 8.0 x 8.0 cm was instrumented with single internal PZT patch at the centre of the beam as shown in Fig. 4.11. The structure was loaded in different cycles to a maximum loads of 4 kN, 8 kN and 10 kN. Finally, failure occurred during the last loading cycle at 11 kN.

![Experimental set up](image)

**Fig. 4.11 Experimental set up**
Frequency plots were determined at each load condition and first three frequencies were determined as described in earlier cases. The frequencies changes at different load condition are listed in Table 4.6.

**Table 4.6 Comparison of frequencies recorded by embedded PZT sensor of one storey R.C. model**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Undamaged Frequencies(Hz)</th>
<th>At 4 kN</th>
<th>At 8 kN</th>
<th>At 10 kN</th>
<th>11 kN (failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Freq.</td>
<td>%change</td>
<td>Freq.</td>
<td>%change</td>
</tr>
<tr>
<td>f₁</td>
<td>130</td>
<td>128</td>
<td>1.5</td>
<td>124</td>
<td>4.6</td>
</tr>
<tr>
<td>f₂</td>
<td>172</td>
<td>171</td>
<td>0.58</td>
<td>170</td>
<td>1.16</td>
</tr>
<tr>
<td>f₃</td>
<td>242</td>
<td>242</td>
<td>0.0</td>
<td>241</td>
<td>0.41</td>
</tr>
</tbody>
</table>

It is observed that the change in the first frequency at failure stage (very severe damage) is 10.76 %, which is comparable to case III. However, the structure being fundamentally different, exact comparison with previous cases is difficult.

**Case Study VII: Model of one Storey Building on Shake Table**

Similar R.C. frame as described in Case study VI was tested on shake table. To induce damage, the frame was vibrated on shake table at frequency 20 Hz and varying amplitudes of 1 mm, 4 mm, 8 mm and 12 mm respectively. The frequency changes at different shaking amplitudes are listed in Table 4.7.
Table 4.7 Comparison of frequencies recorded by embedded PZT sensor of one storey R.C. model tested on shake table

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Undamaged Frequencies(Hz)</th>
<th>At 1 mm</th>
<th>At 4 mm</th>
<th>At 8 mm</th>
<th>At 12 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>Freq. %change</td>
<td>freq %change</td>
</tr>
<tr>
<td>f₁</td>
<td>130</td>
<td>127.8</td>
<td>1.7</td>
<td>123.1</td>
<td>5.3</td>
</tr>
<tr>
<td>f₂</td>
<td>172</td>
<td>170.6</td>
<td>0.80</td>
<td>169.4</td>
<td>1.50</td>
</tr>
<tr>
<td>f₃</td>
<td>242</td>
<td>242</td>
<td>0.0</td>
<td>240.8</td>
<td>0.50</td>
</tr>
</tbody>
</table>

It is observed that the change in the first frequency at failure stage (very severe damage) is 12.80 %, which is greater than case study VI. Since reductions in EI were spread through the entire structure, the reduction in stiffness was more prominent.

Based on above case studies, following conclusions were drawn:

(i) There is greater change in first natural frequency compared to other natural frequencies after damage.

(ii) It is certain that there are negligible changes in frequencies after incipient damage. Hence, incipient damage cannot be surely detected using global techniques.

(iii) Frequency changes after damage also depends upon the span and geometry of the structure.

(iv) It may be possible that frequency changes for the same level damage in same structure are different, depending upon how the damage originated in the structure.

(v) It is impossible to predict the severity of damage based on frequencies change alone. It may be possible that greater change in frequencies may occur for a lower level of damage in a structure compared to a higher level of damage in any other structure.
(vi) There are noticeable changes in frequencies for moderate to severe damage. Hence, global technique is suitable for prediction of presence of moderate to severe damage.

(vii) A rational method should be developed to measure the severity in term of original stiffness.

The purposes of these experiments are mainly to serve as a motivation for the proposed integration technique. Hence, some of the previous conclusions have simply been stated for the purpose of emphasis. Also, when global technique based on frequencies change is used for damage detection, these factors should also be considered.

### 4.3 PRESENCE OF INCIPIENT DAMAGE

The complex electro-mechanical admittance \( \bar{Y} \) of the coupled system has been discussed in detail in Chapter 2. Eq. (2.5) is based on 1D impedance model. Bhalla and Soh (2004a,b) further extended it to 2D systems by introducing the concept of ‘effective impedance’ and derived the following expression for admittance for a square PZT patch:

\[
\bar{Y} = G + Bj = 4\omega j \frac{l^2}{h} \left[ \frac{e_{33}^T}{(1-\nu)} \left( \frac{2d_{31}^2 Y_E}{(1-\nu)} + \frac{2\nu Z_{a,eff}}{Z_{s,eff} + Z_{a,eff}} \right) T \right]
\]  \hspace{1cm} (4.2)

where, the term \( T \) is the updated complex tangent ratio (ideally \( \tan(\kappa l/\kappa l) \)) and \( l \) is the half length of the patch. Further, admittance expressed in Eq (4.2) was split (Bhalla and Soh, 2004a, b) into two parts as
\[
Y = Y_p + Y_A
\]  
(4.3)

where, \(Y_A\) is the ‘active’ component and \(Y_p\) the ‘passive’ component. \(Y_p\) was broken down into real and imaginary as

\[
Y_p = G_p + B_p j
\]  
(4.4)

where

\[
G_p = \frac{4\omega l^2}{h} \left\{ \delta_{53}^T + K \eta \right\}
\]  
(4.5)

\[
B_p = \frac{4\omega l^2}{h} \left\{ \epsilon_{33}^T - K \right\}
\]  
(4.6)

and

\[
K = \frac{2d_{31}^2 Y_E}{(1 - \nu)}
\]  
(4.7)

\(G_p\) and \(B_p\) can be predicted with reasonable accuracy if the conductance and the susceptance signatures of the PZT patch are recorded in ‘free-free’ condition, prior to its bonding or embedded to the host structures. Hence, the PZT contribution can be filtered off from the raw signatures and the active component deduced as,

\[
Y_A = Y - Y_p = \frac{8 \omega l^2}{h(1 - \nu)} \left( \frac{Z_{a,eff}}{Z_{s,eff} + Z_{a,eff}} \right) T j
\]  
(4.8)

where, \(Z_{a,eff} = x_a + y_a j\) the effective impedance of the PZT patch is in short circuited condition.
Substituting $Y^E = Y^E(1 + \eta j)$ and $T = r + tj$ into Eq. (4.8), and rearranging the various terms, the effective impedance of the structure, $Z_{s,\text{eff}} = x + y j$ can be extracted as (Bhalla and Soh, 2004b)

$$x = \frac{M(x_a R - y_a S) + N(x_a S + y_a R)}{M^2 + N^2} - x_a$$

(4.9)

$$y = \frac{M(x_a S + y_a R) - N(x_a R - y_a S)}{M^2 + N^2} - y_a$$

(4.10)

where,

$$M = \frac{B_d h}{4\omega Kl^2} \quad \text{and} \quad N = -\frac{G_d h}{4\omega Kl^2}$$

(4.11)

$$R = r - \eta t \quad \text{and} \quad S = t + \eta r$$

(4.12)

All structural systems have their own impedance characteristics. Table 4.8 shows the variation of the real and imaginary components, $x$ and $y$ respectively for some simple systems. Real structures will have their own characteristic variations. To simplified analysis, Bhalla and Soh (2004 a,b) proposed a simplified “identification” approach, when a real structure is identified as a combination of basic elements, after comparing impedance variation with Table 4.8. In general, the two components (real and imaginary) represented by Eq.(4.9) and Eq. (4.10) of the extracted effective drive point (EDP) impedance may not display an ideal behaviour, such as pure stiffness or pure mass or pure damper. There are variations of the resistive term ($x$) and the reactive term($y$) with the frequency similar to a combination of the basic elements of Table 4.8. The unknown
structure can be idealized as an equivalent structure (as series or parallel combination of basic elements) and equivalent parameters can be determined. The equivalent parameters vary with the stiffness of the structure. If damage/crack occurs due to loading or any other reason, variation of equivalent parameters indicate about the presence of incipient damage/crack Bhalla and Soh (2004 b). Hence, our purpose is to extract the equivalent parameters in real time to capture a crack/incipient damage in structure.

Hence, the equivalent stiffness of structure can be determined in a suitable range of frequencies in the damaged and the undamaged states and after comparing with the standard complex combination. These complex combinations can be obtained by combining the basic elements in a number of different ways (series, parallel and a mixture). Hixon (1988) prepared a table for some possible combination of basic element. A plot the impedance plots (x, y vs frequency), which is reproduced in Table 4.8. A conclusion about patterns can be drawn after comparing the extracted component with result presented in this Table. Since in whole process, it takes very less time to acquire signature and do computation, it is possible that the analysis part can be completed on a personal computer and thus the PZT signature analysis can be performed online.

4.4 EXPERIMENTAL SET UP

Application of this methodology was done on a simply supported 4m steel beam (ISBM 150 as per Indian Standards). The steel beam was instrumented with one PZT patch at 120.4 cm from right support, as shown in Fig. 4.12 (a). The artificial damages were induced in seven stages, as illustrated in Fig. 4.12 (b).
Table 4.8 Mechanical impedance of combinations of spring, mass and damper (Bhalla, 2004)

<table>
<thead>
<tr>
<th>No.</th>
<th>COMBINATION</th>
<th>x</th>
<th>y</th>
<th>x vs Freq.</th>
<th>Y vs Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>c</td>
<td>$-\frac{k}{\omega}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>c</td>
<td>$m\omega$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0</td>
<td>$m\omega - \frac{k}{\omega}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>c</td>
<td>$m\omega - \frac{k}{\omega}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>$\frac{c^2}{c^2 + (\omega m)^2}$</td>
<td>$\frac{(\omega m)^2}{c^2 + (\omega m)^2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0</td>
<td>$-\frac{1}{\omega k - (\omega m)^2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>$\frac{c^2}{c^2 + (\omega k - \omega m)^2}$</td>
<td>$-\frac{\omega k - \omega m}{c^2 + (\omega k - \omega m)^2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>c</td>
<td>$\frac{\omega m k}{k - \omega m}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>$\frac{c^2}{c^2 + (\omega m)^2}$</td>
<td>$\frac{m - k(c^2 + \omega^2 m^2)}{\omega [c^2 + (\omega m)^2]}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>$\frac{c^2}{c^2 + (\omega k)^2}$</td>
<td>$\frac{\omega m (c^2 + \omega^2 k^2) - k^2}{c^2 + (\omega k)^2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>$\frac{cm^2 \omega^3}{c^2 + (\omega m - k/\omega)^2}$</td>
<td>$\frac{m \omega^3 c^2 - k (\omega m - k/\omega)^2}{c^2 + (\omega m - k/\omega)^2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>$\frac{c^2}{c^2 + [(\omega m - k)/\omega]^2}$</td>
<td>$\frac{-\omega (k - m \omega)}{c^2 + [\omega (k - m \omega)^2]}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>$\frac{ck^2 / \omega^3}{c^2 + (\omega m - k/\omega)^2}$</td>
<td>$\frac{-\omega m (\omega m - k/\omega) + \frac{c^2 k}{\omega m}}{c^2 + (\omega m - k/\omega)^2}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the first stage damage, a hole of 0.6 cm diameter was drilled in the flange at 1.6 cm from the right corner. In the second stage, a new hole of 0.6 cm diameter was drilled in the flange at a distance of 1.5 cm from the left corner. In the third stage, the first hole was enlarged by drilling another hole of 0.6 cm diameter at a distance of 1.7 cm from the left corner of the flange. In the fourth stage, a cut of 6.5 cm length was made through the entire thickness of the flange starting from the left corner. In the fifth stage, the cut was extended across the entire width of the flange. In sixth damage stage, the severity of the previous damage was increased by increasing the depth of the cut to one forth depth of the web. In the seventh stage, the depth of the cut was increased till the middle of the web. Since the artificial damages were created in seven stages in steel beam, the conductance and the susceptance were measured at each stage. Presence of damage in the steel beam was detected using the EMI technique. The admittance signatures (consisting of the conductance and the susceptance) of the PZT patch were obtained in the frequency range 100-160 kHz using the Agilent E4980A LCR meter (Agilent Technologies, 2009), for the undamaged and the seven damage states. Fig. 4.13 shows the plot between the conductance (G) and frequency at frequency range 100 kHz to 120 kHz for the undamaged stage and the first three damage stages. It is observed that the conductance changed significantly at the first damage stage itself. The shifting of the frequency peak clearly indicates the presence of damage. The steel beam was idealized as an equivalent structure (series or parallel combination of basic elements), and the equivalent system parameters were determined. After taking the signature of PZT patch, “x” and “y” were extracted using the Eq.4.9 and Eq 4.10. and graphs were drawn between x,y vs frequency. These graphs are closely examined using the Table 4.8 and the appropriate combination
was chosen. Finally equivalent parameter was extracted. This procedure has been well established by Bhalla and Soh (2004). A close examination of the extracted component in the frequency range 140-160 kHz suggested that the system behaviour was similar to a parallel spring combination, for which (Bhalla and Soh, 2004a, b),

\[ x = c \quad \text{and} \quad y = -k / \omega \] (4.13)

using Eq. (4.13) and the actual impedance plot, the average “equivalent” system parameters were worked as \( c = 8.94 \text{ Ns/m} \) and \( k = 6.63 \times 10^6 \text{ N/m} \) for the undamaged state. The analytical plots of \( x \) and \( y \) obtained by these equivalent parameter match well with their experimental counterparts, as shown in Fig. 4.14. This procedure was repeated for all seven damage states to extract the equivalent system parameters. These parameters are listed in Table 4.9. It is clear from table that value of ‘\( k \)’ increased with damage severity while that value of ‘\( c \)’ decreased. At such high frequencies, a local damage may soften few modes and at the same time, stiffen few others. This phenomenon leads to lateral shifting of the peaks in the conductance signature (Naidu and Soh, 2004). At such high frequencies, not much can be predicted theoretically. It is also observed that although the EMI technique acts very well during the initial phase of damage, it is not able to distinguish very well the severe damage states (eg. stage 5 onwards). Similar trend was reported by Tseng and Naidu (2002). The change of the equivalent parameter in case of severe damages can be noted to be very negligible. In contrast, the change in first three frequencies (obtained from global vibration technique) is listed in Table 4.10.
Table -4.9 Variations of equivalent stiffness and damping with damage for steel beam

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Damage state</th>
<th>Equivalent Stiffness (k) (N/m)</th>
<th>Equivalent Damping (c) (Ns/m)</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>undamaged</td>
<td>6.53 x 10^6</td>
<td>8.94</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>State-1</td>
<td>6.73 x 10^6</td>
<td>8.50</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>State-2</td>
<td>6.83 x 10^6</td>
<td>8.45</td>
<td>5.4</td>
</tr>
<tr>
<td>4</td>
<td>State-3</td>
<td>7.04 x 10^6</td>
<td>8.39</td>
<td>7.2</td>
</tr>
<tr>
<td>5</td>
<td>State-4</td>
<td>7.05 x 10^6</td>
<td>8.35</td>
<td>7.4</td>
</tr>
<tr>
<td>6</td>
<td>State-5</td>
<td>7.06 x 10^6</td>
<td>8.32</td>
<td>7.5</td>
</tr>
<tr>
<td>7</td>
<td>State-6</td>
<td>7.09 x 10^6</td>
<td>8.30</td>
<td>7.8</td>
</tr>
<tr>
<td>8</td>
<td>State-7</td>
<td>7.09 x 10^6</td>
<td>8.30</td>
<td>7.8</td>
</tr>
</tbody>
</table>

While there is negligible change in the frequencies till first two/three damage states, a much higher change in equivalent parameters (Table 4.9) identified by the EMI technique can be easily noticed. However, as the severity of damage increases further, advantage of the EMI technique decreases. Contrary to this, as the severity of damage increases, the clarity provided by the global technique increases. When, the EMI technique fails to provide any new information, global technique begins to act more efficiently. Hence, the two techniques complement to each other.
Fig. 4.12 (a) Steel beam for verification (b) Various damaged state from 1-7
Table -4.10 Variations of first three natural frequencies with damage for steel Beam

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Damage state</th>
<th>First natural frequency / (% change)</th>
<th>Second natural frequency / (% change)</th>
<th>Third natural frequency / (% change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>undamaged</td>
<td>45 (-)</td>
<td>190 (-)</td>
<td>410 (-)</td>
</tr>
<tr>
<td>2</td>
<td>State-1</td>
<td>45 (0.0)</td>
<td>189 (0.52)</td>
<td>410 (0.00)</td>
</tr>
<tr>
<td>3</td>
<td>State-2</td>
<td>45 (0.0)</td>
<td>189 (0.52)</td>
<td>408 (0.49)</td>
</tr>
<tr>
<td>4</td>
<td>State-3</td>
<td>41 (8.9)</td>
<td>185 (0.97)</td>
<td>402 (1.95)</td>
</tr>
<tr>
<td>5</td>
<td>State-4</td>
<td>39 (13.3)</td>
<td>182 (4.21)</td>
<td>399 (2.68)</td>
</tr>
<tr>
<td>6</td>
<td>State-5</td>
<td>37 (17.8)</td>
<td>179 (5.79)</td>
<td>392 (4.39)</td>
</tr>
<tr>
<td>7</td>
<td>State-6</td>
<td>36 (20.0)</td>
<td>174 (8.42)</td>
<td>387 (5.61)</td>
</tr>
<tr>
<td>8</td>
<td>State-7</td>
<td>34 (24.4)</td>
<td>170 (10.52)</td>
<td>380 (7.32)</td>
</tr>
</tbody>
</table>
Advantage of the combined approach is the same sensor is used in both the techniques. The incipient damage can be detected at very initial stage using the EMI technique and for the global technique, the change in frequencies is noticeable after the fourth damage stage.

Fig. 4.14 Mechanical impedance of steel beam  
(a) Real part vs. frequency (b) Imaginary part vs. frequency
4.5 CONSISTENCY OF DAMAGE INDEX BASED ON EQUIVALENT “k”

A simply supported 4m steel beam (ISBM 150 as per Indian Standards) differ from that covered in Section 4.4, was instrumented with three PZT patches, the first PZT patch was located at 1m from left support, the second PZT patch at 1m the from right support and the third PZT at 60 cm from right support. The first and the second PZT patches were symmetrically located. Equivalent stiffness was determined of all three PZT using method described in Section 4.4 of Chapter 4. Equivalent stiffness was found $6.74 \times 10^6$ N/m, $8.74 \times 10^6$ N/m and $6.98 \times 10^6$ N/m for first, second and third PZT patches respectively. An artificial damage was induced by drilling the hole in the flange of diameter 0.4cm at mid span exactly. Again equivalent stiffness were determined, which were found $7.044 \times 10^6$ N/m, $9.32 \times 10^6$ N/m and $7.25 \times 10^6$ N/m for first, second and third PZT patches respectively. Percentage changes in equivalent stiffness were found 6.0, 6.63 and 3.98 respectively. It is observed that if symmetry is maintained, percentage change in equivalent stiffness will be approximately same after damage, even equivalent stiffness was differ initially and percentage change in equivalent stiffness vary with distance of sensor.

4.6 CONCLUDING REMARKS

This chapter illustrated the variation of natural frequencies for same level of damage in different structures. For incipient damage, there was clear frequency shift and considerable change in equivalent parameters identified by the EMI technique. Even inducing a very shall artificial damage in terms of a drill hole was successfully detected.
It can be concluded that presence of incipient damage can be detected using EMI technique. It is also observed that although the EMI technique is very sensitive to the incipient damage, it fails to distinguish between moderate to severe damages. As the severity of the damage increases, performance of the EMI technique decreases. It is the point where we can start to apply the global technique, which will described in next chapter.
CHAPTER 5

DETERMINATION OF DAMAGE LOCATION

5.1 INTRODUCTION

It is essential to take appropriate re-strengthening measure after detecting the presence of damage in a structure. But this is possible only when exact locations of the damage are known. To locate the damage, a continuous characteristic function of the structure, whose value undergoes change with damage, should be used. The value of the function should possibly be known at each point of structure so that it is possible to determine the location of the damage after comparing the values of this parameter before and after the damage. These functions may be strain energy, mode shapes, deflection and stiffness. But it is very difficult to determine these parameters accurately at each point. Mode shape is a very sensitive parameter because it is continuous function of structure, provided is continuously known along the structure without any interpolation, which is difficult. Due to this reason, it is very difficult to determine the incipient damage using mode shapes as parameter. The mode shapes are generally drawn by joining the deflections at distantly located sensors, which does not represent accurate value. If damage exists between two sensors or away from the sensors, it is not possible to draw the actual accurate mode shape between these two sensors. Zhou et al. (2007) found that the location of damage can be determined with accuracy equal to the distance between sensors, verifying the reasoning presented above.
In this Chapter, a new method is proposed, by which experimental mode shapes of a structure can be determined accurately using a single surface-bonded PZT patch. The incipient damage is located using the EMI technique and moderate to severe damage are located using experimental mode shape. In case of moderate to severe damage, the location can be determined as desired accuracy using single piezo sensor.

5.2 LOCATION OF INCIPIENT DAMAGE

Basic drawback of global technique is that it cannot detect the incipient damage. Hence, no question of location of these level damages. The incipient level damages may be critical for structures like aerospace components and nuclear plants. Here, the location of the incipient damage is determined using the EMI technique.

Admittance signature of PZT patch can be obtained using the EMI technique. Equivalent stiffness and damping can be extracted by method described in Section 4.3 of Chapter 4. These equivalent stiffness and damping are functions of several parameters like adhesive bonding layer thickness, type of material and boundary conditions. If two PZT patches bonded on exactly same type of specimen, applying other parameters same, their signature and extracted equivalent parameters might still differ because it is impossible to control all the governing parameters which affect the signature of PZT patches. For example, it is impossible to control the adhesive bond layer thickness practically because it is in micrometers. But once PZT patches are bonded on surface of structure, the percentage change of equivalent parameter with damage is approximately of similar magnitude. These percentage changes in equivalent parameters vary with distance
between damage and PZT patches. Hence, the damage can be located where these changes will be highest. The location of damage can be specified after choosing the highest change and next highest change in equivalent stiffness of sensors. Once, the damage position is traced between two sensors, it approximate position can be located taking linear variations. Let the damage be traced between \( n^{th} \) and \( (n+1)^{th} \) PZT sensors and distance between these two PZT patches is “\( x \)”. If the percentage change in equivalent stiffness on \( n^{th} \) sensor is \( y_1 \), \( (n+1)^{th} \) sensor is \( y_2 \), the approximate location of damage from the \( n^{th} \) sensor is given by

\[
d = \frac{y_2}{y_1 + y_2} x
\]  

(5.1)

where, 
\( d \) = distance of damage from \( n^{th} \) sensor
\( x \) = distance between sensors where damage located

5.3 EXPERIMENTAL SET UP TO DETECT THE INITIAL DAMAGE

The beam described in Section 4.4 was instrumented with 11 PZT patch at interval of 33.33 cm as shown in Fig. 5.1. The artificial damages were induced in seven stages as described and illustrated in Fig. 4.12 (b), and first three damages were treated as incipient, as clear from Table 4.10, where the first few frequencies changed negligibly. The admittance signatures (consisting of the conductance and susceptibility) of the each PZT patch were acquired in the frequency range 100-160 kHz using the Agilent E4980A LCR meter (Agilent Technologies, 2009), for the undamaged and the first three damage states.
Fig. 5.1 Experimental set up for incipient damage

Fig 5.2 shows the plot between the conductances (G) in the frequency range 100 kHz to 120 kHz for the undamaged stage of all eleven PZT sensors. It is observed that no specific trend is found in conductance with variation of distance of sensor. The steel beam was idealized as an equivalent structure (series or parallel combination of basic elements), and the equivalent system parameters were determined as described in Chapter 4 using Eq. 4.13.

![Fig 5.2 Signature of 11 PZT patches, Conductance vs frequency](image-url)
These parameters are listed in Table-5.1 for first three damage states. It is seen from Table 5.1 that there are very small changes in ‘k’ of PZT no 9, 10 and 11, which were located very far. Percentage changes of k increase with damage severity and decrease as the distance increase from PZT sensor. Fig 5.3 shows the plot of the change of k of different sensors for three damage state.

**Table 5.1 Percentage variation of Equivalent Stiffness of all PZT sensors**

<table>
<thead>
<tr>
<th>PZT No</th>
<th>Undamaged k(N/m) × 10^6</th>
<th>Damage State 1 k(N/m) × 10^6</th>
<th>Change(%)</th>
<th>Damage State 2 k(N/m) × 10^6</th>
<th>Change(%)</th>
<th>Damage State 3 k(N/m) × 10^6</th>
<th>Change(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT 1</td>
<td>6.56</td>
<td>6.86</td>
<td>4.7</td>
<td>6.97</td>
<td>6.3</td>
<td>7.44</td>
<td>13.5</td>
</tr>
<tr>
<td>PZT 2</td>
<td>8.67</td>
<td>9.47</td>
<td>9.2</td>
<td>9.73</td>
<td>12.3</td>
<td>10.54</td>
<td>21.6</td>
</tr>
<tr>
<td>PZT 3</td>
<td>7.65</td>
<td>8.51</td>
<td>11.2</td>
<td>8.83</td>
<td>15.5</td>
<td>9.53</td>
<td>24.6</td>
</tr>
<tr>
<td>PZT 4</td>
<td>5.97</td>
<td>6.41</td>
<td>7.4</td>
<td>6.67</td>
<td>11.6</td>
<td>7.20</td>
<td>20.7</td>
</tr>
<tr>
<td>PZT 5</td>
<td>8.45</td>
<td>8.92</td>
<td>5.6</td>
<td>9.26</td>
<td>9.7</td>
<td>10.03</td>
<td>17.5</td>
</tr>
<tr>
<td>PZT 6</td>
<td>6.78</td>
<td>7.04</td>
<td>3.9</td>
<td>7.28</td>
<td>7.4</td>
<td>7.70</td>
<td>13.6</td>
</tr>
<tr>
<td>PZT 7</td>
<td>8.56</td>
<td>9.44</td>
<td>3.3</td>
<td>9.09</td>
<td>6.2</td>
<td>9.37</td>
<td>9.5</td>
</tr>
<tr>
<td>PZT 8</td>
<td>6.53</td>
<td>6.73</td>
<td>2.9</td>
<td>6.83</td>
<td>5.4</td>
<td>6.83</td>
<td>7.2</td>
</tr>
<tr>
<td>PZT 9</td>
<td>8.56</td>
<td>8.65</td>
<td>1.1</td>
<td>8.66</td>
<td>1.2</td>
<td>8.66</td>
<td>1.2</td>
</tr>
<tr>
<td>PZT 10</td>
<td>6.63</td>
<td>6.68</td>
<td>0.8</td>
<td>6.69</td>
<td>0.9</td>
<td>6.69</td>
<td>0.9</td>
</tr>
<tr>
<td>PZT 11</td>
<td>7.89</td>
<td>7.92</td>
<td>0.4</td>
<td>7.92</td>
<td>0.4</td>
<td>7.92</td>
<td>0.4</td>
</tr>
</tbody>
</table>
To locate the damage, the PZT patches undergoing first two highest percentage changes were chosen. It is found that maximum percentage changes of sensor were for PZT 2 and PZT 3 after damage state 1. Same trend was repeated for the damage state 2 and the damage state 3. Hence, it concluded that damage location was between sensor 2 and sensor 3. Using Eq 5.1, the exact location of damage from PZT sensor 3 was calculated. It was found that calculated value was 18.3 cm from 2\textsuperscript{nd} PZT sensor which compares well with the actual value of 13.3 cm from the second PZT sensor. Hence, the damage is reasonably located.

![Fig. 5.3 Variation of percentage change of equivalent stiffness of different PZT sensor](image)

In the same way, the damage location after damage state 2 and the damage state 3, calculated from the sensor 2\textsuperscript{nd} were found as 18.6 cm and 17.7 cm. These compare well with actual location of 13.3 cm respectively. Hence, the incipient damage can be located
using this method and moderate to severe damage could be located using global dynamic technique. In case of incipient damage, if the sensor network is dense, greater will be the accuracy of damage location.

5.4 EVALUATION OF EXPERIMENTAL MODE SHAPE

The general equation of motion for a dynamic system is (Chopra, 1996)

\[ [M][\ddot{x}] + [C][\dot{x}] + [K][x] = [F(t)] \]  \hspace{1cm} (5.2)

where, \([M]\) is the mass matrix, \([C]\) the damping matrix, \([K]\) the stiffness matrix, \([\ddot{x}], [\dot{x}], [x]\) and \([x]\) the acceleration, the velocity and the displacement vectors respectively, and \([F(t)]\) the force vector. For free vibration, \([F(t)]\) is zero, hence

\[ [M][\ddot{x}] + [C][\dot{x}] + [K][x] = 0 \]  \hspace{1cm} (5.3)

The solution of Eq. (5.3) yields the \(N\) natural frequencies \(\omega_n\) (\(n = 1, 2, 3, \ldots, N\)) of vibration. The roots \(\omega_n^2\) of Eq. (5.3) are known as the eigen values. For every natural frequency \(\omega_n\), there corresponds a mode shape vector \(\Phi_n\) satisfying Eq. (5.3). The eigen value problem does not fix the absolute amplitude of the vector \(\Phi_n\), but only provides the relative shape. Corresponding to the \(n^{th}\) natural frequency \(\omega_n\), there are \(N\) independent displacements. The mode shape \(\Phi_n\) is the displacement profile of the structure (at the \(N\) points) at the particular frequency \(\omega_n\). The displacement at any point of structure is the summation of the displacement due to all modes. If the displacement of any point is measured, the relative contribution of each mode can be separated by FFT (Paz, 1999). Hence, if the time history of each point is known, mode shape can be drawn by joining the
displacement at the corresponding frequency $\omega_n$. To draw the mode shape exactly, displacement is required continuously along the entire structure. But ideally, it is impossible to install sensors at each point on the structure. On the other hand if the sensors are installed at considerable distance apart, graphical interpolation will not yield the true mode shape.

In general, to induce free vibration in a structure, very small magnitude loads are required for excitation due to which the assumption of linear behaviour of the structure is satisfied. In this chapter, the strain mode shapes of the structures are derived experimentally. For a linear structure, by reciprocal-displacement theorem, the deflection at point ‘n’ due to a unit load acting at point ‘m’ is numerically equal to the deflection at point ‘m’ due to the unit load acting at point ‘n’ (Reddy, 1996). Hence, the strain response of any point of the structure can be measured by a single sensor (fixed at a particular point) and applying the fixed or unit magnitude load at the point of interest. By changing the point of application of that fixed load, the time history can be determined for each of the $N$ points. From the recorded time history, the natural frequency can be determined by FFT and the ordinate of the FFT curve corresponding to that frequency represents the relative maximum displacement at that point. The typical time histories of PZT sensor in terms of output voltage is shown in Figs. 5.4, 5.6, 5.8 and the FFT of these time histories are shown in Figs. 5.5, 5.7, 5.9.

The mode shape so derived will be the curvature mode shape, since the PZT patch measures surface strain, as given by,
\[ \varepsilon = y''d \]  \hspace{1cm} (5.4)

where, \( y'' \) is the curvature (second derivative of displacement) and \( d \) the distance of the PZT patch from the neutral axis. The number of mode shapes which can be extracted, will depend upon the minimum sampling interval of instrument by which time history is recorded and the magnitude of the frequency.

**Fig. 5.4** Typical time history, measured by PZT sensor

**Fig. 5.5** FFT of time history
First two/three mode shapes are generally sufficient to predict location and severity of damage, if accurately determined. Accuracy depends how many nodes the structure is
divided into, if more nodes are considered, there will be less interpolation error and greater accuracy (Naidu and Soh, 2004).

![Graph 1](image1)

**Fig. 5.8** Typical time history, measured by PZT sensor

![Graph 2](image2)

**Fig. 5.9** FFT of time history
5.5 LOCATION OF MODERATE TO SEVERE DAMAGE

The Chapter 4 focused on the presence of damage in the structure. Once there is evidence of the presence of damage, the location of the damage can be determined using the global dynamic techniques if the damage has grown into moderate to severe magnitude. The experimental strain (or curvature) mode shapes of the structure can be used to determine the location of damage. If a bending moment is applied to a structure, resultant stress is proportional to the curvature of the structure. Hence, changes in curvature before damage and after damage indicate the presence, location and severity of damage. If curvature changes at a cross-section, it indicates the presence and location of damage (Pandey and Biswas, 1991). The magnitude of change in curvature indicates the severity. Same can be applied for two dimensional structures like plate. If an element undergoes damage, the curvature of the element will undergo change. The natural frequencies are identified and the corresponding modes shapes derived to determine the change of curvature for computing appropriate damage index. For a single damage scenario, greatest value of the damage index will indicate the location of damage. Once damage has been located between two nodes, the distance between the nodes can be further subdivided into suitable number of elements which can be treated as new nodes and the process be continued till damage is located with desired accuracy. In case of beam or one dimensional structures such as the one shown in Fig. 5.10, the damage index for each element can be defined as change in curvature of any element, as

\[
(D.I)_i = \sum_{n=1}^{N} \left( C_{\text{damaged}} - C_{\text{undamaged}} \right)
\]  

(5.5)
where \( C_{undamaged} \) is the curvature before damage, \( C_{damaged} \) is the curvature after damage and \( N \) is the number of the mode shape used in the determination of the damage index.

In the same way, the damage index for 2D plate like structure can be defined. The plate can be divided into suitable number elements using a grid. Considering a typical plate of \( N_x, N_y \) elements along \( X \) and \( Y \) directions as shown in Fig. 5.11, following can be defined

\[
[x]_{j,k}^{i} = i^{th} \text{ strain mode shape ordinate before damage for node } (j,k) \tag{5.6}
\]

\[
[X]_{j,k}^{i} = i^{th} \text{ strain mode shape ordinate after damage for node } (j,k) \tag{5.7}
\]
The average curvatures along the \(X\) and the \(Y\) directions for the undamaged and the damaged cases are respectively given as

\[
P^{x,i}_{j,k} = \left( x^{i}_{j,k} + x^{i}_{j+1,k} \right)/2 \quad \text{(Before damage)} \tag{5.8}
\]

\[
P^{x,i}_{j,k} = \left( X^{i}_{j,k} + X^{i}_{j+1,k} \right)/2 \quad \text{(After damage)} \tag{5.9}
\]

Similarly,

\[
P^{y,i}_{j,k} = \left( x^{i}_{j,k} + x^{i}_{j,k+1} \right)/2 \quad \text{(Before damage)} \tag{5.10}
\]

\[
P^{y,i}_{j,k} = \left( X^{i}_{j,k} + X^{i}_{j+1,k} \right)/2 \quad \text{(After damage)} \tag{5.11}
\]

where

\[
p^{x,i}_{j,k} = \text{average curvature of } i^{th} \text{ strain mode shape along } X \text{ axis before damage at node } (j, k)
\]

\[
P^{x,i}_{j,k} = \text{average curvature of } i^{th} \text{ strain mode shape along } X \text{ axis after damage at node } (j, k)
\]

\[
p^{y,i}_{j,k} = \text{average curvature of } i^{th} \text{ strain mode shape along } Y \text{ axis before damage at node } (j, k)
\]

\[
P^{y,i}_{j,k} = \text{average curvature of } i^{th} \text{ strain mode shape along } Y \text{ axis after damage at node } (j, k)
\]

Now, a damage index can be defined for the nodes for change in curvature both along \(X\) and \(Y\) direction as

\[
B^{x}_{j,k} = \sum_{i=1}^{m} \frac{p^{x,i}_{j,k}}{P^{x,i}_{j,k}} \tag{5.12}
\]

\[
B^{y}_{j,k} = \sum_{i=1}^{m} \frac{p^{y,i}_{j,k}}{P^{y,i}_{j,k}} \tag{5.13}
\]

\[
B_{j,k} = \left( B^{x}_{j,k} + B^{y}_{j,k} \right)/2 \tag{5.14}
\]
where

\[ B_{j,k}^x = \text{Damage index for node } (j,k) \text{ using change in curvature along } X \text{ axis} \]

\[ B_{j,k}^y = \text{Damage index for node } (j,k) \text{ using change in curvature along } Y \text{ axis} \]

\[ B_{j,k} = \text{Damage index for nodes } (j,k) \text{ using combined change in curvature of the first } m \text{ modes.} \]

Finally, a damage index for the element is defined by summing up the nodal damage indices of the four nodes, i.e.

\[ D_{j,k}^x = \left( B_{j,k}^x + B_{j,k+1}^x + B_{j+1,k}^x + B_{j+1,k+1}^x \right) \]  \hspace{1cm} (5.15)

\[ D_{j,k}^y = \left( B_{j,k}^y + B_{j,k+1}^y + B_{j+1,k}^y + B_{j+1,k+1}^y \right) \]  \hspace{1cm} (5.16)

\[ D_{j,k} = D_{j,k}^x + D_{j,k}^y \]  \hspace{1cm} (5.17)

where

\[ D_{j,k}^x = \text{Damage index for element } (j,k) \text{ using change in curvature along } X \text{ axis}. \]

\[ D_{j,k}^y = \text{Damage index for element } (j,k) \text{ using change in curvature along } Y \text{ axis}. \]

\[ D_{j,k} = \text{Damage index for element } (j,k) \text{ using combined in curvature along } X \text{ and } Y \text{ axis}. \]

Damage location is identified as the location with maximum value of D.

**5.6 EXTRACTION OF STRAIN MODE SHAPES**

The experimental mode shapes of a structure can be extracted using the principle and the methodology described in Section 5.3. Application of this methodology was carried out on a 4m steel beam (ISBM 150 as per Indian Standards) and the mild steel plate of dimensions 1260×630×6.5mm. To determine the damaged and the undamaged experimental modes shapes, the steel beam, which was in simply supported condition, the
PZT patch located at a distance of 120.4 cm from right support was used (Fig. 4.12a). To predict the presence and locate incipient damage, all 11 PZT patches were used using the EMI technique. However, to generate the experimental mode shape, only one PZT was used with the help of the Betti-Maxwell theorem. To generate the experimental strain mode shape of a structure, strain of each point is required at a time and mode shape can be drawn by joining these points. These strains are sum of strain due to each mode. These can be separated by FFT, which gives the relative strain corresponding to each natural frequency. From practical point of view, these points can be limited in number like in case of beam structure, which was divided into 11-segments. Other alternate way, which was used here, is to measure response using one sensor and apply constant exciting force (a ball of weight 200gm falling from 1.5m constant height) applied at all 11 points. In addition, near the damage location, measurements were made at additional points also be make sure smooth curve.

In the present scenario, the structure is divided into 11 nodes. A fixed magnitude load is applied at each of these nodes for excitation (which means the structure is excited by a constant kinetic energy), and the time history of the PZT patches were recorded and converted into frequency response function by FFT. Corresponding ordinate of the FFT curve represents the maximum relative strain for that point. After knowing the strain at these nodes, the mode shape can be drawn with the help of the ordinates of the peaks corresponding to natural frequencies. Artificial damages were induced in seven stages as described in Chapter 4 (Fig. 4.12b). The beam was divided into twelve equal parts resulting eleven nodes where PZT patches were bonded and plus two supports end. At each node, a standard excitation was made to induce the beam into free vibrations, by
dropping a steel ball of 0.2kg from a fixed height of 1.5m. The potential energy converted into strain energy after the impact and the total energy was thus same for each drop. For each drop, the response of the beam was recorded for a period of two seconds using the voltage response of the PZT patch, measured using the Agilent 34411A digital multimeter at 200 µs sampling interval. The experimental set up is shown in Fig. 5.12.

![Experimental Setup](image)

**Fig. 5.12** Experimental Setup

All the measurements were made automatically through programs running in VEE PRO environment. The recorded voltage data was transformed from the time domain to the frequency domain by carrying out FFT in the MATLAB environment. Applying the same procedure, frequency plots were determined at all the eleven nodes. The ordinates of the FFT curves were noted corresponding to the first three bending frequencies. This process was repeated at all the eleven nodes. With the help of these ordinates, first three
bending mode shapes were drawn. Fig 5.13 shows the first undamaged strain mode shape without smoothing. The first three experimental bending frequencies of the steel beam were found to be 45 Hz, 190Hz and 410Hz. The frequencies have been determined analytically also, and result as 38 Hz, 152Hz and 342 Hz, which agree with experimental values. Fig 5.14 shows the first three modes shape for the undamaged and the seven damage states. The same procedure was adopted for the MS steel plate. The experimental set up consisted of the MS plate instrumented with single PZT patch sensor at a distance of 38 cm along X- axis, and 25 cm along Y axis from right corner, as shown in Fig 5.15(a). The plate was simply supported on all the four edges, ensured by attaching a hollow square metallic tube to the plate by epoxy adhesive. The plate was divided into a 5x10 grid, resulting in interior 36 (4 x 9) nodes. To excite the plate with equal energy, a weight of 1 kg was dropped at each node from 1.5 m height.

![Graph](image-url)  
**Fig 5.13** First undamaged bending modes shape of steel beam without smoothing
Fig 5.14 First three bending modes shape of steel beam for various damage stages
(a) Mode 1  (b) Mode 2  (c) Mode 3. 129
Free vibration response was measured at each node using the Agilent 34411A digital multimeter with a sampling interval of 200-micro seconds. The measured data was transformed from the time domain to frequency domain by carrying out FFT in MATLAB environment, as in the case of the beam. The first three natural frequencies of the plate were measured as 20 Hz, 230 Hz and 490 Hz. The value of real part of the FFT was used to draw first three strain mode shapes. The first stage damage was induced by drilling a hole of diameter 55 mm in the plate in the first stage at the distance 300 mm along the X-axis and 200 mm along the Y-axis from left corner, as shown in Fig 5.15(b). Thereafter, the second damage was induced by drilling a hole of diameter 55 mm in the plate at the distance 200 mm along X-axis and 300 mm along Y-axis from right corner. Finally, the third level of damage was induced by increasing the diameter of second hole to 100 mm. First three undamaged modes shape was obtained similar to the beam, as shown in Fig 5.16. First three mode shapes for the first stage damage are shown in Fig. 5.17, for the second stage in Fig 5.18 and for the third stage in Fig 5.19.

5.7 LOCATION OF DAMAGE

After the section of the beam and the plate underwent damage, the curvature changed compared to the undamaged state. To locate the damage, experimental strain modes shapes were directly used. The most advantageous point of using the surface bonded PZT patch is that readings of PZT sensor provide the curvature (or strain) mode shape directly. The damage index was determined for each element of the steel beam and the plate using Eq. 5.5 for the beam for the various damage states. The plot of damage index vs element number as shown in Fig. 5.20 for beam. It can be seen from figure that at the all stages of damage, the damage index was highest at the damaged element compared to other
elements. Damage index increased numerically as the damage severity increased. Same procedure was adopted for the steel plate, where Eq. 5.17 was employed. Fig. 5.21 shows the plot between the damage index and the element number for the three damage states. It is observed that the damage index was highest at the damage location compared to other grid elements.

Fig. 5.15 (a) MS steel plate with PZT sensor (b) Artificial damage in plate.
Fig. 5.16 Mode shapes of plate in undamaged state (a) First mode (b) Second mode (c) Third mode (distance in meter)
Fig 5.17 Mode shapes after 1st stage (a) First mode (b) Second mode (c) Third mode (Distance in meter)
Fig. 5.18 Mode shapes after 2nd stage (a) First mode (b) Second mode(c) Third mode (Distance in meter)
Fig. 5.19 Mode shapes after 3rd stage (a) First mode (b) Second mode (c) Third mode (Distance in meter)
Thus, the damage was correctly identified. In addition, multiple damage locations are also identified. It should be noted that if the experimental mode shapes are used for damage detection, the damage index of the adjacent element is comparable to the damaged element. So, at the location of the damage, it is seen like umbrella type structure. Since damage index value represents for the whole element, if greater accuracy is desired, damage index can be further refined by dividing the damaged element into suitable number of sub elements and till the desired accuracy is achieved. There will be no requirement to determine the damage index for other elements which had lesser damage index in the previous cycle of measurements.

**Fig 5.20** Damage index of steel Beam (damage stage 1-7)
Fig 5.21 Damage index (D.I.) of steel Plate (a) Stage-1 (b) Stage-2 (c) Stage-3
5.8 CONCLUDING REMARKS

Experimental mode shapes were determined by a simple procedure using a single PZT patch for both beam and plate structures. The damage in the steel beam and the MS plate were located using experimental mode shapes. It is found that moderate and severe damage can be located using only single sensor with the aid of the global dynamic technique. Locations of Incipient damage were determined using multiple sensors using the EMI technique. A new approach is thus developed for predicting the incipient, moderate and severe damage by the combined use of the global and local techniques, utilizing the same PZT patch. In the next chapter, severity of damages in structure will be predicted in term of as hair crack, incipient, moderate, severe and very severe damage.
CHAPTER - 6

PREDICTION OF SEVERITY OF DAMAGE

6.1 INTRODUCTION
After detecting the correct location of the crack/damage, the next step is to determine its severity so as to take the corrective measures in time. Also, there are several sensitive structures like aerospace and nuclear structures, where even a minor crack/damage could have an adverse effect on the structure’s performance. For these structures, it is necessary to determine the severity in terms of loss of the original stiffness. In case of high severity also, degree of severity should be known to take decision about replacement of part of the structure. In this Chapter, a mathematical formulation is derived to predict the severity of damage in terms of stiffness of the original structure. Generally, there are many terms defined about the severity like hair line crack, incipient damage, moderate damage, severe damage and very severe damage. But these are relative and vary from structure to structure. For example, for the same level damage in aerospace and civil structure, the damage in the aerospace structure will be more severe where as for civil structure, it may be treated as incipient damage. Hence, the best approach will be to define the severity in term of loss of the original stiffness, which will be an absolute measure. Stiffness can be classified into bending stiffness, axial stiffness, shear stiffness and torsion stiffness. But basic point is that if any one stiffness is known, others can be determined easily. However, it is easy to evaluate the bending stiffness of the structure experimentally. Hence, in this chapter, emphasis is paid to bending stiffness only to evaluate the damage severity.
6.2 FORMULATION FOR SEVERITY OF DAMAGE

In Eq. (5.2), let a mode shape function be designated $\Phi(x)$, and the amplitude of the mode shape be denoted by the generalized coordinate $Z(t)$. Hence, the displacement at any point can be expressed as

$$y(x,t) = \phi(x)Z(t) \quad (6.1)$$

in which $\phi(x)$ is the shape function. This effectively reduces the beam to the single degree of system (equivalent of the continuous system or infinite degree of system). Thus, the harmonic variation of the generalized coordinate in free vibration is given as

$$y(x,t) = \phi(x)Z_0 \sin \omega t \quad (6.2)$$

Eq. (6.2) expresses the assumption that the shape of the vibrating beam does not change with time, only the amplitude of motion varies, thus it varies harmonically in a free-vibration condition. At the point of maximum displacement,

$$y(x,t) = \phi(x)Z_0 \quad (6.3)$$

For a beam the strain energy of this flexural system is given by

$$V = \frac{1}{2} \int_0^L EI(x) \left( \frac{\partial^2 y}{\partial x^2} \right)^2 dx \quad (6.4)$$
where, \( L \) is the length of the beam, \( E \) the Young’s modulus of the material of the structure and \( I \) the moment of inertia. Thus, substituting the assumed shape function and letting the displacement amplitude take its maximum value leads to

\[
V_{\text{max}} = \frac{1}{2} Z_0^2 \int_0^L EI(x) \left( \Phi'^2 \right) dx
\]

(6.5)

In general, the total energy of the system will distribute in vibrating into different mode shapes. However, 80 - 90% energy is normally distributed among the first three or four mode shapes alone. If the structure is damaged, it is assumed that there will be no change of distribution of energy in different modes if the excitation force and the boundary conditions remain unchanged. Hence, we can treat the share of the strain energy to be same in the corresponding mode shape before damage and after damage. The total strain energy will be same in both damaged and undamaged case due to the fact that the height of the free fall during the test will be the same.

If any damage occurs in the structure at any section, modulus of elasticity will reduce more at that section compared to others and there will be change of average value of the modulus of elasticity. This change reflects the severity of damage. Here, only average value of ‘\( E \)’ of whole structure has been determined. If any section of the structure is damaged, the tendency of that point is to undergo greater displacement compared to the undamaged case. However, due to the inertia and the adhesive forces, the neighboring elements, which are less damaged, will oppose and also undergo somewhat greater displacement to balance the equilibrium. Hence, this affects the entire mode shape of the
structure, which reflects the presence of damage. As the severity of damage increases, the strain at the damaged section will increase. This will also increase the maximum value of $Z_0$. Since the response can be measured directly by the sensor, proportional value of $Z_0$ can read directly from mode shape. $Z_0$ is the maximum displacement of a particular mode shape and can be measured directly from the extracted mode shape. In Chapter 5, mode shapes were extracted using constant excitation force. If the procedure to determine the mode shape remains same, the amplitude of mode shapes increases as the damage increases. Hence, increasing value of $Z_0$ is as indicator of damage. This is because the mode shape is curvature mode shape and curvature generally increases with reduction of EI accompanied by damage. In general, $Z_0$ monotonically increases as the damage increases, if $Z_0$ included, it increases the accuracy of prediction. However it is difficult to determine exact value of this parameter. But to predict the location of damage, experimental mode shape has to be determined. Hence, it is included here to calculate the damage index. Further, another advantage is that it predicts the severity more accurately and disadvantage is that it is very difficult to be determined its exact value.

Since it is possible to control the total input energy, by conversation of energy,

$$\left( V_{\text{max}} \right)_{\text{undamaged}} = \left( V_{\text{max}} \right)_{\text{damaged}} \quad (6.6)$$
\[ \left[ \frac{1}{2} (Z_0^2)_{\text{undamaged}} \left( \int_0^L (EI(x))_{\text{undamaged}} (\Phi^*(x))^2_{\text{undamaged}} \, dx \right) \right] = \left[ \frac{1}{2} (Z_0^2)_{\text{damaged}} \left( \int_0^L (EI(x))_{\text{damaged}} (\Phi^*(x))^2_{\text{damaged}} \, dx \right) \right] \]

Integrating above Eq. by parts with \((EI(x))_{\text{undamaged}}\) as first function, Left hand side become

\[ \frac{1}{2} (Z_0^2)_{\text{undamaged}} \left[ EI(x)_{\text{undamaged}} \int_0^L (\Phi^*(x))^2_{\text{undamaged}} \, dx \right] - \int_0^L \left[ \frac{d(EI(x))_{\text{undamaged}}}{dx} \times \int (\Phi^*(x))^2_{\text{undamaged}} \, dx \right] \, dx \] (6.7)

Differentiation of \(EI(x)_{\text{undamaged}}\) is gives finite value of damaged sections and its values will be zero for undamaged sections. If a structure is damaged, damaged sections are limited compared to undamaged sections. Hence, the II term of Eq. 6.7 will be zero. For damaged case, it can be neglected.

or

\[
\frac{(EI(x))_{\text{undamaged}}}{(EI(x))_{\text{damaged}}} = \frac{\left( Z_0^2 \right)_{\text{damaged}} \left( \int_0^L (\Phi^*(x))^2_{\text{damaged}} \, dx \right)}{\left( Z_0^2 \right)_{\text{undamaged}} \left( \int_0^L (\Phi^*(x))^2_{\text{undamaged}} \, dx \right)} = \eta \] (6.8)

If the structure is divided into \(N\) segments with \(N+1\) node, the Eq. 6.8 can be written as

\[
\frac{(EI(x))_{\text{undamaged}}}{(EI(x))_{\text{damaged}}} = \frac{\left( Z_0^2 \right)_{\text{damaged}} \left( \sum_{i=1}^{N} \int_{a_i}^{a_{i+1}} (\Phi^*(x))^2_{\text{damaged}} \, dx \right)}{\left( Z_0^2 \right)_{\text{undamaged}} \left( \sum_{i=1}^{N} \int_{a_i}^{a_{i+1}} (\Phi^*(x))^2_{\text{undamaged}} \, dx \right)} = \eta \] (6.9)

\(\Phi^*(x)\) can be determined directly by PZT patches before and after the damage and by integration of \([\phi^*(x)]^2\) with respect to \(x\) gives the area of square of the mode shape. The value of percentage change of stiffness can be determined by Eq. (6.9). Hence, damage
severity can be determined in terms of the original stiffness after drawing the experimental mode shape of structure and the finding area of the square of the mode shape and the maximum relative amplitude of the mode shapes.

Similar expression was given by Stubbs and Kim (1995), which is reproduced below.

\[
\frac{(EI(x))_{\text{undamaged}}}{(EI(x))_{\text{damaged}}} = \left( \frac{\int_0^L \phi^2(x) \, dx}{\int_0^L (EI(x))^2 \, dx} \right)_{\text{undamaged}} \times \left( \frac{\int_0^L (EI)^2 \phi^2(x) \, dx}{\int_0^L (EI(x))^2 \, dx} \right)_{\text{damaged}}
\]

(6.10)

\(I\) \quad \text{II}

Eq. 6.8 differs from equation given by Stubbs and Kim (1994) with respect to following points.

1. Mode shape extracted by proposed method (section 5.6), was used to determine the severity of damage. Taking the height of fall constant in case of damaged and undamaged case and applying the rule of conservation of energy, the term II of Eq. (6.9) get cancelled out.

2. If the structure is damaged, magnitude of maximum displacement of mode shapes increases and it is function of severity of damage. Its value will be higher for severe damage. This is reflected in Eq. 6.8 but not in equation developed by Stubbs and Kim (1994).

3. Eq. 6.8 is very simple in application and no complex mathematical calculation is required. It can be used practically. However, the equation developed by Stubbs and Kim require a lot of statistical variable and mathematical calculations.
4. Eq. (6.8) can be used directly for plate structures because PZT sensors extract two dimensional curvatures along the two principal directions.

6.3 EXPERIMENTAL VALIDATION AND RESULT

Validation of the theoretical developments is done on the steel beam and the plate described in Chapters 4 & 5. Using the experimental damaged and undamaged mode shapes at different damage states, the percentage change of stiffness was calculated using the Eq. 6.8. Area of the square of the mode shape gives the direct value of integration and values of \( Z_0 \) can be read directly from mode shape and are listed in Table 6.1 & 6.2. The severity of damage of steel beam after various stage of damage is listed in Table 6.1. In the same way, severity of damage of MS plate is listed in Table 6.2. It is observed that as we increase the damage severity artificially, it percentage stiffness decreases, which is clearly reflected from the tables.

Table -6.1 Variation of stiffness ratio with damage for steel beam

<table>
<thead>
<tr>
<th>S.No</th>
<th>Damage State</th>
<th>Mode amplitude ( Z_0 )</th>
<th>( \eta ) =ratio of current stiffness with undamaged stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>State-1</td>
<td>18.21</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>State-2</td>
<td>18.27</td>
<td>0.94</td>
</tr>
<tr>
<td>3</td>
<td>State-3</td>
<td>18.33</td>
<td>0.92</td>
</tr>
<tr>
<td>4</td>
<td>State-4</td>
<td>18.42</td>
<td>0.88</td>
</tr>
<tr>
<td>5</td>
<td>State-5</td>
<td>18.51</td>
<td>0.85</td>
</tr>
<tr>
<td>6</td>
<td>State-6</td>
<td>18.65</td>
<td>0.83</td>
</tr>
<tr>
<td>7</td>
<td>State-7</td>
<td>18.75</td>
<td>0.81</td>
</tr>
</tbody>
</table>
Table -6.2 Variation of stiffness ratio with damage for MS Plate

<table>
<thead>
<tr>
<th>S.No</th>
<th>Damage State</th>
<th>Mode amplitude Z₀</th>
<th>$\eta =$ratio of current stiffness with undamaged stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stage-1</td>
<td>25.35</td>
<td>0.98</td>
</tr>
<tr>
<td>2</td>
<td>Stage-2</td>
<td>25.93</td>
<td>0.93</td>
</tr>
<tr>
<td>3</td>
<td>Stage-3</td>
<td>27.2</td>
<td>0.83</td>
</tr>
</tbody>
</table>

6.4 CONCLUDING REMARKS

The severity of damage is computed of the steel beam in seven stages and that of MS plate in three stages, completely in term of the original bending stiffness. The severity may be considered as hair crack, incipient, moderate, severe and very severe corresponding to change in stiffness 1%, 5%, 10%, 20% and 50%. The presence, location and severity of damage have been already calculated. Practical application of developed techniques will be covered in next chapter.
CHAPTER -7

INTEGRATION OF PZT’S GLOBAL AND LOCAL RESPONSES WITH ANN

7.1 INTRODUCTION
It is easy to detect the presence, location and severity of crack/damage in simple structures using traditional parameters like frequencies and mode shapes. Apart from frequency and mode shape, there are several other parameters, which change with the damage severity. Brownjohn (1979) investigated the use of structural damping as a possible symptom for damage detection. Apart from frequency, damping ratio is also parameter, which changes with damage; however the applicability of damping for locating damage is limited.

This Chapter covers practical application of the methods and techniques developed in the previous chapters on RC frame and integrate the basic idea of using local cum global response of PZT patches with ANN.

7.2 RC FRAME: DETAILS OF SPECIMEN, INSTRUMENTATION AND TESTING
The test specimen consisted of a two-storey RC frame of column height 0.625 m (each storey), beam length 1.68 m and cross sectional dimension of 10x10 cm, made from M30 grade concrete. Fig. 7.1 shows the specimen and the instrumentation. Before embedding, the PZT patches, of size 10x10x0.3mm, conforming to grade PIC 151 (PI Ceramic, 2009), were first encapsulated in cement mortar resulting in an overall dimensions of 25x25x25mm, as explained earlier.
Fig 7.1 (a) Location of PZT patches (b) Cross-sectional area of R.C.frame
The encapsulated sensor is well prepared to withstand the harsh conditions at the time of construction. The sensors, six in number, were placed in the formwork of the specimen as shown in Fig. 7.1, and casting done as usual. Vibrators were also used at the time of the casting. After a curing of 28 days, all the sensors were found to be working well.

Fig. 7.2 shows the measurement set up consisting of the test frame structure, Agilent 34411A digital multimeter (Agilent Technologies, 2009), a personal computer (PC), shake table and Agilent 4980 precision LCR meter (Agilent Technologies, 2009). To determine the experimental natural frequencies (global dynamic technique), the structure was excited by striking with a hammer and free vibration response was measured using the digital multimeter, at a sampling interval of 500 microseconds, using programs running in VEE PRO environment.
Fig. 7.3 shows the typical plot of the voltage across the PZT patch 1 with time. It can be observed that the signal to noise ratio is sufficiently high, typically of the order of 20. The measured data was transformed from time domain to frequency domain by carrying out FFT in MATLAB environment.

Fig. 7.4 shows the plot of frequency vs voltage obtained by this method at healthy state condition from the PZT patch 1. The first three natural frequencies of the frame structure are 40 Hz, 115 Hz and 235 Hz in the healthy state condition. The frequencies of the frame structure, determined numerically using the ANSYS 9, were found as 42.65Hz, 120.63 Hz and 250.94 Hz. Thus, the experimental frequencies agree reasonably well with the numerical frequencies, which establish that the embedded PZT patches act as a global dynamic sensor properly. Another salient feature of the investigation is that the same PZT
patches were utilized for obtaining the damping ratio (for the first resonance frequency) using the half power width method (Chopra, 1996), as

\[ \xi = \frac{1}{2} \left( \frac{f_2 - f_1}{f} \right) \]  

(7.1)

where, \( f \) is the experimental resonance frequency of the structure and \( f_1 \) and \( f_2 \) are the end point of the half power width of the resonance frequency (the frequencies at the 0.707 times resonance amplitude). Damping ratio can be determined from free or forced vibration test without necessitating the measurement of the applied force. If the severity of damage increases (more cracks in the structure) the damping ratio also increases.

Fig. 7.4 FFT of the voltage response from PZT patch 1.
As far as the EMI technique is concerned, the admittance signatures of the PZT patches were recorded in the frequency range 60-200 kHz using LCR meter. The real and the imaginary parts of the structural mechanical impedance were determined using Eqs. 4.9 to 4.12. A close examination of the extracted components in the frequency range 150-200 kHz suggested that the system behaviour was similar to a parallel spring damper system, as represented by Eq. 4.13.

The average “equivalent” system parameter identified by PZT patch ‘1’ were worked as $c = 27.08$ Ns/m and $k = 1.08 \times 10^6$ N/m in undamaged state. The analytical plot of $x$ and $y$ obtained by the equivalent parameter match well with their experimental counterparts as shown in Fig. 7.5. Similar procedures were repeated for all six PZT patches and equivalent system parameters were extracted for all damage states.

In order to induce structural damage, the frame was vibrated on the shake table at near the first frequency (40 Hz), so that resonance conditions are ensured, thereby inflicting maximum damage. The amplitude was varied to 1 mm, 4 mm, 8 mm, 12 mm and 16mm to induce damages of varying severity. Measurements were recorded after each excitation, both for global dynamic as well as the EMI technique, as explained for the case of the healthy structure. For purpose of this study, the damage was classified as hairline crack (not visible by naked eye, however, can be seen with the help of high resolution magnifying glass), incipient (cracks clearly not visible by naked eye, but can be recognised after careful inspection or simple magnified glass), moderate (cracks clearly visible without magnifying glass), severe (crack width widen to few mm) and very severe (structure with at least one severe crack in every member).
At the initial stage, the amplitude was maintained as 1 mm, for a period of 30 second. After the excitation, the frame was investigated thoroughly and all the hairline cracks were

Fig. 7.5 Mechanical impedance of R.C. frame as identified by PZT patch 1

(a) Real part vs frequency
(b) Imaginary part vs frequency

At the initial stage, the amplitude was maintained as 1 mm, for a period of 30 second. After the excitation, the frame was investigated thoroughly and all the hairline cracks were
marked. The shaking amplitude was then increased to 4 mm at same frequency and time duration was increased to 2 minutes. To induce the moderate damage, the amplitude was increased to 4.5mm, 5mm, 5.5mm, 6mm, 6.5mm, 7mm, 7.5mm and 8mm successively for periods of 45 second, one minute, one and half minute and two minutes respectively. Same procedure was adopted to induce severe and very severe damage, the amplitude and duration was varied under full observation by trial and error. The final amplitude for moderate damage was 8mm, time span was two minutes and for severe damage, the amplitude was 12 mm, and time span was 2.5 minutes. Finally, for very severe damage, the amplitude was increased to 16 mm for a period of four minutes. Fig. 7.6 shows the condition of the frame after the test.

Fig. 7.7 shows the variation of conductance (G) vs frequency after each excitation level for PZT patch 1. From this figure, it is observed that the conductance plots altered significantly immediately after the incipient damage, when the amplitude of excitation was restricted to 1mm only. This is further evident from Table 7.1, which lists the equivalent stiffness and the damping parameters of PZT patch ‘1’ after the various excitation levels. The stiffness changes are very much discernible. The changes in the natural frequencies measured by PZT patch ‘1’ at various damage levels are listed in Table 7.2. It is observed from the table that changes in natural frequencies at incipient damage (lower amplitudes) are negligible, especially up to 8 mm amplitude. It is therefore very difficult to detect the incipient damage based on frequency change. Hence, the presence of the incipient damage can be easily detected by using EMI technique whereas the global dynamic technique could at best detect moderate and severe damage only.
Fig. 7.6 Experimental observations of various levels of damages.
(a) Overall frame (b) Zoomed view of top portion
Table -7.1 Variations of Equivalent Stiffness and Damping with Damage for PZT Patch

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Damage state</th>
<th>Equivalent Stiffness (k) (N/m)</th>
<th>Equivalent Damping (c) (Ns/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base line-Amplitude 0 mm</td>
<td>$1.08 	imes 10^6$</td>
<td>27.26</td>
</tr>
<tr>
<td></td>
<td>(undamaged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Amplitude-1 mm</td>
<td>$1.03 	imes 10^6$</td>
<td>27.93</td>
</tr>
<tr>
<td></td>
<td>(hair crack)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Amplitude-4 mm</td>
<td>$0.96 	imes 10^6$</td>
<td>28.50</td>
</tr>
<tr>
<td></td>
<td>(incipient damage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Amplitude-8 mm</td>
<td>$0.89 	imes 10^6$</td>
<td>28.99</td>
</tr>
<tr>
<td></td>
<td>(moderate damage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Amplitude-12 mm</td>
<td>$0.88 	imes 10^6$</td>
<td>29.05</td>
</tr>
<tr>
<td></td>
<td>(severe damage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Amplitude-16 mm</td>
<td>$0.87 	imes 10^6$</td>
<td>29.08</td>
</tr>
<tr>
<td></td>
<td>(Very severe damage)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It should also be noted that after moderate damage (amplitude 8 mm), any further change in the value of equivalent stiffness and damping is very small. This fact is also highlighted by Tseng and Naidu (2002). Hence together, the EMI technique and the global dynamic technique form complimentary systems and work when the counterpart is not very effective.

**Table 7.2 Comparisons of change in natural frequencies at different damage states**

<table>
<thead>
<tr>
<th>Natural frequency</th>
<th>Base line</th>
<th>Amplitude: 1mm (hairline crack)</th>
<th>Amplitude: 4 mm (incipient)</th>
<th>Amplitude: 8 mm (moderate)</th>
<th>Amplitude: 12 mm (severe)</th>
<th>Amplitude: 16 mm (Very severe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>40</td>
<td>39.5</td>
<td>39.1</td>
<td>38.2</td>
<td>36</td>
<td>34</td>
</tr>
<tr>
<td>2nd</td>
<td>115</td>
<td>114</td>
<td>112.5</td>
<td>105</td>
<td>103</td>
<td>98</td>
</tr>
<tr>
<td>3rd</td>
<td>235</td>
<td>232</td>
<td>230</td>
<td>225</td>
<td>218.5</td>
<td>210</td>
</tr>
</tbody>
</table>

The damping ratios were determined of each PZT patch at different damage states for the first natural frequency. The damping ratio at the undamaged state, hairline crack, moderate damage, severe damage and very severe damaged are listed in Table 7.3. It is clear from the table that there are negligible changes in damping ratio for incipient damages. But for moderate to severe damage, the changes are significant and easily discernible. This pattern is similar to the first few frequencies of the global dynamic techniques. It may be further noted that the change in damping ratio will be more if the damage is located near the sensor but variation in damping ratio measured by different sensors for same level damage can be ignored. However, changes in damping ratio with damage for a particular sensor are noticeable. Hence, damping ratio can be treated as
parameter to differentiate damage severity especially for moderate to severe damage. The main advantage here is that damping ratio can be measured without measuring the excitation force. The damping ratio is a representation of the region surrounding of the PZT patch. After damage identification, the next section deals with damage localization and severity assessment using ANN.

Table 7.3 Variation of Damping Ratio of PZT Patches with Different Damage State

<table>
<thead>
<tr>
<th>Damping ratio</th>
<th>Base line</th>
<th>Amplitude: 1 mm (hairline crack)</th>
<th>Amplitude: 4 mm (incipient)</th>
<th>Amplitude: 8 mm (moderate)</th>
<th>Amplitude: 12 mm (severe)</th>
<th>Amplitude: 16 mm (Very severe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezo no-1</td>
<td>0.042</td>
<td>0.042</td>
<td>0.044</td>
<td>0.051</td>
<td>0.055</td>
<td>0.057</td>
</tr>
<tr>
<td>Piezo no-2</td>
<td>0.0414</td>
<td>0.042</td>
<td>0.043</td>
<td>0.049</td>
<td>0.056</td>
<td>0.058</td>
</tr>
<tr>
<td>Piezo no-3</td>
<td>0.0425</td>
<td>0.042</td>
<td>0.044</td>
<td>0.05</td>
<td>0.054</td>
<td>0.06</td>
</tr>
<tr>
<td>Piezo no-4</td>
<td>0.04</td>
<td>0.041</td>
<td>0.042</td>
<td>0.048</td>
<td>0.054</td>
<td>0.059</td>
</tr>
<tr>
<td>Piezo no-5</td>
<td>0.043</td>
<td>0.043</td>
<td>0.047</td>
<td>0.053</td>
<td>0.059</td>
<td>0.061</td>
</tr>
<tr>
<td>Piezo no-6</td>
<td>0.04</td>
<td>0.04</td>
<td>0.043</td>
<td>0.047</td>
<td>0.053</td>
<td>0.055</td>
</tr>
</tbody>
</table>

7.3. APPLICATION OF ANN FOR DAMAGE ASSESSMENT
This section describes the application of the ANN for improved damage assessment. The proposed neural network is a back-propagation network (Nelson and Illingworth, 1990), comprising of an input layer, an output layer and a hidden layer. In the training process, a single hidden layer was used and the number of hidden neurons was decided in the
training process by successively increasing the number of neurons by the trial and error till least error is achieved for the output.

Generally, incipient damage occurs as localized hairline cracks. It is assumed here that between two sensors, damage will be located at one point only. If there are two or more damages between two sensors, the proposed method gives the average location of damage from the sensor. The comprehensive configuration of the proposed neural network is shown in Fig. 8.8. The inputs consist of the coordinates of the sensor, percent change of the equivalent stiffness and the equivalent damping (EMI technique), percent change in frequencies and percent change in the damping ratios (Global vibration technique). The outputs are severity (no damage, hairline crack, initial crack, moderate damage, severe damage and very severe damage) and location of crack/damage (x-coordinate, y coordinate). A total of 3200 data points were generated to develop the proposed ANN. For example, to induce the severe damage, the amplitude was increased to 8.5mm, 9mm, 9.5mm, 10mm, 10.5mm, 11mm, 11.5mm and 12mm successively for periods of 45 second, one minute, one minute and 15seconds, one and half minute, one minute and 45seconds, and two minutes respectively and each time all input parameters was noted. Same procedure was adopted to induce hairline crack, initial crack, moderate and very severe damage, the amplitude and duration was varied under full observation by trial and error. Vibration period was varied from 15 second to 4 minute and amplitude increment interval was 0.25 mm. 75% of this data was used for training purpose and 25% was used for testing. The back propagation feed forward model with logistic function was used for training. There were three layers, one input, one hidden, and one output layer. 5000 epoch
were used for training purpose to reach optimum level. There are 2-3% root mean square error (RMS) in testing results and 1-2% in training. If one more hidden layer was added, RMS error decreases to 1-1.5% in training but testing result was increased 4-5%. Hence, optimize configuration of ANN was found with three layer.

In present case, there are six sensors having 12 coordinates (x, y) and 12 changes in equivalent stiffness and damping (in percent form), average percentage change in first three frequencies and the corresponding damping ratios. Since the frequencies and the damping ratios are global properties of structure, their values at a specific level damage, obtained from each sensor were approximately same, hence average values of six sensors were considered. So that, there were total 28 input (12 co-ordinates, 12 equivalent stiffness and damping, first three frequencies and one damping ratio) and 18 outputs (two coordinates of damage for each sensor and the damage status).

Severity was defined in five levels namely as hair crack, incipient damage, moderate damage; severe damage and very severe damage as explained earlier. At each load condition, these inputs data were extracted from each sensor at different damage severity. A MATLAB tool box was used for the ANN. Validation of the ANN was done after training. The ANN was tested with separate inputs other than used in training, which are shown in Table 7.4. It is clear from the table that the all the damages types and locations were predicted by the ANN correctly. The major damages are shown in Fig. 8.6 were correctly identified and quantified.
Fig. 7.8 Configuration of ANN
### Table 7.4 Damage Location Accuracy

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Predicted by ANN</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Location (from first PZT)</td>
<td>Severity</td>
</tr>
<tr>
<td>1</td>
<td>11 cm in left direction</td>
<td>incipient</td>
</tr>
<tr>
<td>2</td>
<td>25 cm in right direction</td>
<td>moderate</td>
</tr>
<tr>
<td>3</td>
<td>37 cm in right direction</td>
<td>severe</td>
</tr>
</tbody>
</table>

#### 7.4 DISCUSSION

It can be observed that the same PZT sensors were used to determine the lower natural frequencies using global technique and the admittance signature using the EMI technique. Since PZT sensors perform well in low and high frequencies range, both techniques are thus meaningfully integrated to monitor the health of structures locally as well as globally. Severity and location of damage/crack can be determined using the ANN trained, global as well as local data. Also, the proposed technique can be used on any type of structure like beams, frames, trusses and bridges due to the small size of the PZT patches and their ability to detect the incipient damage compared to accelerometer, which are conventionally used for dynamic data extraction. Compared to accelerometers, the PZT patches are extremely low cost. The embedded sensor used here is expected to be more durable and long lasting than the surface-bonded counterpart. Since both incipient and severe damage can be assessed using this technique, which can be universalized for any level of damage. Since there are no limitations of sensor in preparing the ANN, it can be used for any no of sensors and any type of structure. The proposed ANN was developed on elementary frame structure and coordinates of sensors were considered in non-
dimensional form (% of span). Generally, buildings are combination of frames. Hence, considering the real structure as combination of elementary frames, one by one whole building can be monitored. Hence, it can be extended to frames of similar geometry. For other structures, we may be required to train a specific network.

7.5 LIMITATIONS OF PROPOSED ANN

1. If two or more damages exist between two sensors, proposed method gives the average location of damage from the sensor. This is the basic drawback of proposed ANN.

2. Configuration of proposed ANN varied from structure to structure.

3. There are several inputs and outputs, a lot of data are required for training purpose.

4. Proposed ANN can be generalized only for a specific type of structures.

7.6 CONCLUDING REMARKS

The case study covered in this chapter demonstrates that the embedded PZT sensor can be used satisfactorily with global dynamic techniques as well as in the local EMI technique. The damage can be localized and the severity can be determined easily using ANN. The PZT patches can be embedded at the time of construction of the structures. Proposed new technique is applicable on simple as well as complex structures, where traditional techniques fail. Another advantage of proposed techniques is high sensitivity in case of complex structures also.
CHAPTER -8

CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

There are four aspects for complete health monitoring of structures; namely the presence, the location, the severity of the damage and the post damage remaining life of the structure. Conventionally different techniques are used for each aspect and also different types of sensors and hardware. This thesis embodies the research work carried out for complete structural health monitoring and non-destructive evaluation using PZT sensors only. The conventional approach is not only costly and complex but also less sensitive and less accurate to predict the location of damages. Basic aim of this research work was to develop the new approach by integration of the local and the global dynamic techniques, such that the end product is cost effective, sensitive and simple in use, and utilizes one type of sensor only.

The major novelty in the present research is that for the first time, the PZT patches are used as sensors in the global technique (low frequency) as well as in the high frequency EMI technique simultaneously and the evaluation of damage severity is done in term of original stiffness of structure. Complete monitoring is achieved using the same PZT sensor. The integrated approach enables simple detection of incipient level damage as well as more realistic quantification of moderate to severe damage.
The following sections outline the major contributions, conclusions and recommendations stemming out from this research work.

**8.2 RESEARCH CONCLUSIONS AND CONTRIBUTIONS**

This research works has successfully integrated the global dynamic technique with the local EMI technique utilizing the same PZT patch as the key element. The major conclusions and the contributions arising from the research can be summarized as:

1. Conventionally, surface bonded PZT patches are used to monitor the health of structures. There are several difficulties like protection from harsh environment and external wiring associated with the surface bonded PZT patches. In this research, possibility of an embedded PZT sensor has been investigated which can be embedded in structure at the time of construction. It is successfully demonstrated that the embedded sensor acts well in both the global dynamic technique and the EMI technique. Simple low cost digital multi-meter is used to measure the response of the embedded sensor.

2. A simple low cost experimental technique has been developed to directly extract the experimental strain mode shapes of the structures using surface bonded PZT patches. Experimental mode shapes extracted using the proposed technique require less interpolation and are obtained using single PZT sensor. Resolution of ordinates can be controlled as per desired accuracy. The technique uses surface bonded or embedded PZT sensor. First three experimental mode shapes of four meter steel beam ISMB 150 and MS plate were extracted successfully using proposed technique.
3. Occurrence of all levels of damage can be detected using proposed technique. The incipient damage can be detected using the EMI technique and moderate to severe damage using the global dynamic technique. Experimental validation was done on four meter steel beam (ISMB 150). It is also demonstrated that both techniques complement each other.

4. Apart from detection, damage ranging from incipient to near failure (severe) can be located and quantified using the proposed technique. Incipient damage can be located using extracted equivalent parameters from the PZT signatures of various sensors. Moderate to severe damages can be located using extracted experimental mode shape. Basic advantage of proposed technique is that location of damage can be predicted with desired accuracy. Once the damage is located approximately, its exact location can also be traced accurately using proposed method.

5. Severity of damage has been quantified in term of original stiffness using the proposed technique. Conventional methods fail to differentiate the damage in terms of original stiffness. A new algorithm was developed to determine the severity of damage using experimental mode shapes. The developed algorithm is simple in use and requires simple mathematical calculations.

6. An integrated SHM approach has been proposed for implementation in real-life situations. This approach combines the EMI and the global techniques for SHM with the aid of ANN. Equivalent stiffness identified using the EMI technique and the frequencies and the damping ratio obtained using global dynamic technique are used to train the ANN. Practical application of above approach was successfully done on a
model of two stories R.C. frame. Presence, locations and severity of damages were evaluated successfully.

Proposed approach can be implemented for on-line monitoring of structure. Only signatures of PZT are required to analysis the health of structure, which can be collected by proper wireless net working. Signatures of PZT patches can be collected at the time of natural catastrophe like earthquake, rain and tsunami. Continuous monitoring is possible using the proposed technique, which will be helpful to understand the behavior of structure for research purpose.

8.3 RECOMMENDATIONS FOR FUTURE WORK

Present research work can be further extended as follows:

1. A relation may be developed between equivalent stiffness and equivalent damping (identified by PZT patch) and the actual static stiffness and damping of the structure respectively.

2. In this research, the studies have been conducted on model structures. It is recommended that the studies may be extended to real life structures such as buildings and bridges. Long term studies may be performed to assess the effects of damage on the equivalent system parameters identified by the PZT patch in the case of real structures.

3. Future studies may focus on the theoretical aspect of the equivalent system parameters and their relation with material and geometry of the structure.
4. Future studies may also focus on the aspect of energy harvesting so as to make the way for self-driven autonomous sensors, with integrated processing and wireless transmission units.
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JOURNAL


BOOK CHAPTER

CONFERENCE:


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