

BASELINE FREE APPROACH FOR INTEGRATED GLOBAL CUM LOCAL STRUCTURAL HEALTH MONITORING USING PIEZO-TRANSDUCERS

JASHANJEET RANDHAWA



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JUNE 2023**

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by

JASHANJEET RANDHAWA

Department of Civil Engineering

Submitted

in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2023

CERTIFICATE

This is to certify that the thesis titled “**BASELINE FREE APPROACH FOR INTEGRATED GLOBAL CUM LOCAL STRUCTURAL HEALTH MONITORING USING PIEZO-TRANSDUCERS**” which is being submitted by **Mr. JASHANJEET RANDHAWA** for the fulfillment of the requirements for the award of degree of **Doctor of Philosophy**, is a record of the student’s own work carried out at the **Indian Institute of Technology Delhi** under my supervision and guidance. The matter embodied in this thesis has not been submitted elsewhere for the award of any other degree or diploma.

Dr. Suresh Bhalla

Professor

Department of Civil Engineering

Indian Institute of Technology Delhi

New Delhi

June, 2023

ACKNOWLEDGEMENTS

It is my great pleasure and honor to convey my heartfelt gratitude, obligation, and thankfulness to my supervisor, Dr. Suresh Bhalla, for his tremendous advice, guidance and support during this research. He significantly expands the role of advisor. It has been a privilege to collaborate with Dr. Suresh Bhalla, whose recommendations and critical perspectives have considerably aided me in my effort. I will be eternally thankful for his generosity and assistance, not just to my study but also to my professional development.

I am thankful to Prof. Shashi Mathur, Prof. A.K. Keshari, Prof. Ashok Gupta, and Dr. Ashish Darpe, members of my committee, for their helpful recommendations and advise on my study effort. I am particularly thankful to my colleagues, Sumit and Dattar, for their prompt assistance in carrying out the lab studies.

My gratitude also goes to the entire Civil Engineering professors and other staff members for their encouragement and interest in my research. I am exceedingly thankful to the personnel of the Smart Structures and Dynamics Laboratory (SSDL), as well as the departmental and central libraries, for supplying books, journals, and other materials that enabled this research.

I'd want to express my deepest appreciation to Mr. Lal Singh and the other technicians who graciously gave technical assistance during the lab work. It would not have been feasible to complete the experimental task so successfully without their assistance and realistic recommendations, in addition to the pleasant working environment at the Structures Lab. I'd also want to thank the other members of the Indian Institute of Technology Delhi's support team, who either actively or passively helped to my research.

Finally, I'd want to express my gratitude to my wife “Sakshi” and my parents for their support and efforts. Their encouragement and support laid the groundwork for me to flourish and succeed. My gratitude has to go to my sister for eagerly embracing my failures and successes.

Jashanjeet Randhawa

ABSTRACT

Structural health monitoring (SHM) techniques can be divided broadly into global (for moderate to severe damage) and local (for incipient damage). The global techniques are further divided into categories based on measuring static displacement, strain, etc., or dynamic modal parameters like natural frequencies, mode shapes, modal damping, etc. Some of the most popular local conventional non-destructive evaluation (NDE) methods are ultrasonic, guided waves and acoustic emission using a single or array of mobile transducers and local SHM technique like the modern electro-mechanical impedance (EMI) technique using permanently installed smart piezoelectric lead zirconate titanate (PZT) material patches as sensors/actuators. All the currently prevalent techniques heavily rely on signals obtained from the structure's current condition compared to those from the pristine condition (baseline signals) and thus connect variation in signals characteristics to damage in terms of location and severity. While this strategy has proved effective in the laboratory, significant limitations depend on the baseline signal's availability in actual field operations. Most existing structures do not have attributes that correlate to their pristine condition. Even when accessible, operational and environmental changes tend to conceal the impact of damage on signal characteristics. Most crucially, when measuring the status of a structure following an extraordinary event such as an earthquake or a hurricane, baseline data may become useless. Such occurrences may damage the sensors themselves, necessitating replacing them in various positions around the structure. As a result, the main research field of this thesis, baseline-free structural damage detection, can expand the scope of SHM in the circumstances outlined.

The primary objective of this research is to develop integrated global and local baseline-free technique using low-cost smart PZT patches acting as sensors and actuators. Firstly,

the global baseline free gapped smoothing method (GSM) using non-linear functions is employed to detect damages in beam type structures by measuring curvature mode shapes. Secondly, the EMI technique is rendered baseline free using polarization properties of PZT patch's employed in EMI technique's framework. This renders the proposed approach sensitive to local damage and easily applicable to complex structures. Both global and local techniques integrated and experimentally verified with the help of experiments conducted on an aluminium beam. The results highlight the better damage detecting ability of the proposed integrated approach as compared to existing techniques. Detailed numerical simulation is also carried out using a finite element method employing simulation software, and results establish the feasibility of the proposed approach.

The main contribution of this research is that for the first time, such extensive studies have been carried out on the application of the baseline free health assessment of structures. A new baseline-free assessment approach is proposed for further developing the existing global (modal analysis) and local (EMI) techniques and eliminating their dependency on baseline data by using the same PZT patches acting as actuators and sensors. With the help of this approach, the SHM field can be covered both globally and locally. In addition, an integrated system that operates the very same PZTs by altering the detecting mode may be less complicated in specific ways. Also, global modal analysis experiments which require dynamic forces such as impact hammers (no fixed excitation device) and shakers (fixed or not) to excite the structure in the desired frequency range to develop frequency response functions (FRF), are useless in case of inaccessible or confined structures. The proposed approach involving PZT-patches acting as exciters is a good solution for such cases. In overall, it is hoped that the outcome of this research will be of significant help SHM based on baseline-free domain.

अमूर्त

संरचनात्मक स्वास्थ्य निगरानी (SHM) तकनीकों को मोटे तौर पर वैश्विक (मध्यम से गंभीर क्षति के लिए) और स्थानीय (प्रारंभिक क्षति के लिए) में विभाजित किया जा सकता है। वैश्विक तकनीकों को आगे स्थैतिक विस्थापन, तनाव, आदि, या गतिशील मोडल पैरामीटर जैसे प्राकृतिक आवृत्तियों, मोड आकार, मोडल अवमंदन अनुपात, आदि को मापने के आधार पर श्रेणियों में विभाजित किया गया है। सबसे लोकप्रिय स्थानीय पारंपरिक में से कुछ गैर-विनाशकारी मूल्यांकन (एनडीई) विधियाँ अल्ट्रासोनिक, निर्देशित तरंगों और मोबाइल ट्रांसड्यूसर के एकल या सरणी का उपयोग करके ध्वनिक उत्सर्जन और स्थायी रूप से स्थापित स्मार्ट का उपयोग करके आधुनिक इलेक्ट्रो-मैकेनिकल प्रतिबाधा (ईएमआई) तकनीक जैसी स्थानीय एसएचएम तकनीक हैं। सेंसर/एक्चुएटर के रूप में पीजोइलेक्ट्रिक लेड जिरकोनेट टाइटेनेट (पीजेडटी) सामग्री पैच। वर्तमान में प्रचलित सभी तकनीकें उनकी तुलना में संरचना की वर्तमान स्थिति से प्राप्त संकेतों पर बहुत अधिक निर्भर करती हैं मूल स्थिति (बेसलाइन सिग्नल) से और इस प्रकार स्थान और गंभीरता के संदर्भ में सिग्नल विशेषताओं में भिन्नता को क्षति से जोड़ते हैं। जबकि यह रणनीति प्रयोगशाला में प्रभावी साबित हुई है, महत्वपूर्ण सीमाएँ वास्तविक क्षेत्र संचालन में बेसलाइन सिग्नल की उपलब्धता पर निर्भर करती हैं। अधिकांश मौजूदा संरचनाओं में ऐसी विशेषताएँ नहीं हैं जो उनकी प्राचीन स्थिति से संबंधित हों। सुलभ होने पर भी, परिचालन और पर्यावरणीय परिवर्तन सिग्नल विशेषताओं पर क्षति के प्रभाव को छुपाते हैं। सबसे महत्वपूर्ण बात यह है कि भूकंप या तूफान जैसी असाधारण घटना के बाद किसी संरचना की स्थिति को मापते समय, आधारभूत डेटा बेकार हो सकता है। इस तरह की घटनाएँ स्वयं सेंसर को नुकसान पहुँचा सकती हैं, जिससे उन्हें संरचना के चारों ओर विभिन्न स्थितियों में बदलने की आवश्यकता होती है। नतीजतन, इस थीसिस का मुख्य अनुसंधान क्षेत्र, आधारभूत-मुक्त संरचनात्मक क्षति का पता लगाना, उल्लिखित परिस्थितियों में एसएचएम के दायरे का विस्तार कर सकता है।

इस शोध का प्राथमिक उद्देश्य सेंसर और एक्चुएटर्स के रूप में काम करने वाले कम लागत वाले स्मार्ट PZT पैच का उपयोग करके एकीकृत वैश्विक और स्थानीय बेसलाइन-मुक्त तकनीक विकसित करना है। सबसे पहले, वक्रता मोड आकृतियों को मापकर बीम प्रकार संरचनाओं में क्षति का पता लगाने के लिए गैर-रैखिक कार्यों का उपयोग करते हुए वैश्विक आधार रेखा मुक्त गैप स्मूथिंग विधि (जीएसएम) कार्यरत है। दूसरे, ईएमआई तकनीक को

ईएमआई तकनीक के ढांचे में नियोजित पीजेडटी पैच के ध्रुवीकरण गुणों का उपयोग करके आधारभूत मुक्त प्रदान किया जाता है। यह प्रस्तावित दृष्टिकोण को स्थानीय क्षति के प्रति संवेदनशील बनाता है और जटिल संरचनाओं पर आसानी से लागू होता है। एक एल्यूमीनियम बीम पर किए गए प्रयोगों की मदद से वैश्विक और स्थानीय दोनों तकनीकों को एकीकृत और प्रयोगात्मक रूप से सत्यापित किया गया। परिणाम मौजूदा तकनीकों की तुलना में प्रस्तावित एकीकृत दृष्टिकोण की बेहतर क्षति का पता लगाने की क्षमता को उजागर करते हैं। सिमुलेशन सॉफ्टवेयर का उपयोग करते हुए एक परिमित तत्व विधि का उपयोग करके विस्तृत संख्यात्मक अनुकरण भी किया जाता है, और परिणाम प्रस्तावित दृष्टिकोण की व्यवहार्यता स्थापित करते हैं।

इस शोध का मुख्य योगदान यह है कि पहली बार संरचनाओं के आधारभूत मुक्त स्वास्थ्य मूल्यांकन के अनुप्रयोग पर इस तरह का व्यापक अध्ययन किया गया है। मौजूदा वैश्विक (मॉडल विश्लेषण) और स्थानीय (ईएमआई) तकनीकों को और विकसित करने और एक्चुएटर्स और सेंसर के रूप में कार्य करने वाले समान PZT पैच का उपयोग करके बेसलाइन डेटा पर उनकी निर्भरता को समाप्त करने के लिए एक नया बेसलाइन-मुक्त मूल्यांकन दृष्टिकोण प्रस्तावित है। इस दृष्टिकोण की मदद से, एसएचएम क्षेत्र को विश्व स्तर पर और स्थानीय स्तर पर कवर किया जा सकता है। इसके अलावा, एक एकीकृत प्रणाली जो डिटेक्टिंग मोड को बदलकर वही PZT संचालित करती है, विशिष्ट तरीकों से कम जटिल हो सकती है। इसके अलावा, वैश्विक मोडल विश्लेषण प्रयोग जिसमें आवृत्ति प्रतिक्रिया कार्यों (FRF) को विकसित करने के लिए वांछित आवृत्ति रेंज में संरचना को उत्तेजित करने के लिए प्रभाव हथौड़ों (कोई निश्चित उत्तेजना उपकरण नहीं) और शेकर्स (स्थिर या नहीं) जैसे गतिशील बलों की आवश्यकता होती है, के मामले में बेकार हैं दुर्गम या सीमित संरचनाएं। उत्तेजक के रूप में कार्य करने वाले PZT-पैचों को शामिल करने वाला प्रस्तावित दृष्टिकोण ऐसे मामलों के लिए एक अच्छा समाधान है। कुल मिलाकर, यह आशा की जाती है कि इस शोध के परिणाम बेसलाइन-मुक्त डोमेन पर आधारित एसएचएम के लिए महत्वपूर्ण मददगार साबित होंगे।

TABLE OF CONTENTS

TITLE	PAGE NO.
Certificate	i
Acknowledgements	ii
Abstract	iv
Table of Contents	vi
List of Figures	ix
List of Tables	xiii
List of Symbols	xiv
List of Acronyms	xvii
1. INTRODUCTION	1 to 10
1.1. Background	1
1.2. Motivation	1
1.3. Dynamic SHM Techniques	4
1.3.1. SHM by Modal Analysis	5
1.3.2. SHM by Electro-Mechanical Impedance (EMI) Techniques	6
1.3.3. SHM by Guided Waves	7
1.4. Baseline Free SHM and its Importance	7
1.5. Research Objectives and Scope	9
1.6. Thesis Organization	9
2. LITERATURE REVIEW	11 to 43
2.1. Introduction	11
2.2. Nature of Damage in Structures	12
2.3. SHM Techniques	14
2.3.1. Global SHM Techniques	15
2.3.1.1. Dynamic Techniques	15
2.3.1.2. Static Techniques	19
2.3.2. Local SHM techniques	21
2.4. Electro-Mechanical Impedance (EMI) Technique	23
2.5. Guided (Lamb) Waves	27
2.6. Statistical Baseline-Free Damage Identification Algorithms	32
2.6.1. Based on Global Dynamic	33
2.6.2. Based on Local Guided Lamb Waves	38
2.7. Identification of Research Gaps	41
2.8. Objectives and Scope of Research	42
3. CONVENTION HAMMER VS PIEZO ACTUATORS FOR EXPERIMENTAL MODAL ANALYSIS	44 to 56
3.1. Introduction	44
3.2. Piezoelectricity and Piezoelectric Materials	45
3.2.1. Constitutive Relations	46
3.2.2. Commercial Piezoelectric Materials	46
3.3. Experimental Study	50
3.4. Comparative Assessment of Actuators	52
3.5. Concluding Remarks	56

TITLE	PAGE NO.
4. BASELINE FREE GAPPED SMOOTHING METHOD (GSM): A NUMERICAL STUDY	57 to 75
4.1. Introduction	57
4.2. Modal Analysis	58
4.3. Conventional Curvature Mode Shape Calculations	60
4.3.1. Modes and Mode Shape	60
4.3.2. Mode Shape by Curvature Method	61
4.3.3. Experimental Mode Shape by PZT Patches	61
4.3.4. Damage Detection	64
4.4. Baseline-Free Method: A Numerical Study	64
4.4.1. Damage Severity Investigation	71
4.4.2. Damage Location Investigation	73
4.4.3. Multiple Damage Investigation	74
4.5. Concluding Remarks	75
5. IMPROVED BASELINE-FREE DAMAGE DETECTION USING NON-LINEAR FUNCTIONS IN GAPPED SMOOTHING METHOD (GSM)	76 to 99
5.1. Introduction	76
5.2. Linear Regression of Transformed Data	77
5.3. Polynomial Regression	78
5.4. Cubic Spline	78
5.5. Non-Linear Regression	79
5.6. Non-Linear Gapped Smoothing Method (GSM)	81
5.6.1. Experimental Investigations	83
5.6.2. Experimental Outcome	84
5.6.3. Numerical Simulation	90
5.6.4. Numerical Simulation Results	91
5.7. Concluding Remarks	98
6. LOCAL BASELINE FREE DAMAGE DETECTION USING EMI TECHNIQUE	100 to 124
6.1. Introduction	100
6.2. Methodology	103
6.3. Numerical Investigation	107
6.3.1. Impedance Calculation	110
6.3.2. Simulation Results	110
6.4. Experimental Investigation	116
6.4.1. Experimental Results	119
6.5. Concluding Remarks	124

TITLE	PAGE NO.
7. CONCLUSIONS AND RECOMMENDATIONS	125 to 128
7.1. Conclusions	125
7.2. Original Contributions	126
7.3. Recommendations for Future Research	127
7.4. Limitations	127
List of Publications	129
References	130

LIST OF FIGURES

FIGURE	CAPTION	PAGE NO.
1.1	Damage caused by (a) ageing (Garrettsbridges, 2017) and (b) corrosion in steel truss bridge (Wealthdaily, 2014).	3
2.1	Liang's 1D impedance model (Liang et al., 1994).	24
2.2	Piezoelectric sensor pitch-catch monitoring principle based on guided wave (Wang et al., 2020).	29
3.1	IEEE standard (1987) axes directions for piezoelectric material sheet.	47
3.2	Complete experimental set-up.	51
3.3	Typical (a) time and (b) frequency domain signals acquired using m+p analyzer showing first mode shape (14.08Hz) for simply supported aluminium beam.	52
3.4	Frequency response functions (FRF) for healthy beam when actuator used (a) PZT patch and (b) Hammer.	53
3.5	Frequency response functions (FRF) for damaged beam when actuator used (a) PZT patch and (b) Hammer.	54
3.6	Normalized experimental curvature mode shapes (CMS) evaluated using PZT patch as exciter and traditional hammer actuation (a) Mode 1, (b) Mode 2 and (c) Mode 3.	54
3.7	Modal assurance criterion (MAC) value for comparing hammer and PZT patch mode shapes.	55
4.1	(a) Simple plate excitation/response model, (b) Simple plate response, (c) Simple plate frequency response function (FRF), (d) Overlay of time and FRF and (e) Simple plate sine dwell responses. (Avitabile, 2001)	59
4.2	Healthy beam (a) model and (b) mesh; Damaged beam (c) model and (d) mesh.	65
4.3	Comparing damaged beam first mode for different element size using: (a) Modal Frequency and (b) Displacement.	66
4.4	Damaged beam displacement mode shapes (a) First (b) Second and (c) Third.	68
4.5	(a) Use of probe function for first mode; (b) Plot of deformation/displacement mode shape.	69

FIGURE	CAPTION	PAGE NO.
4.6	Laplacian (L_i) plots (a) 50% Damage severity, (b) 20% Damage severity, (c) 10% Damage severity and (d) 5% Damage severity.	72
4.7	Difference function (δi) (a) 50% Damage severity, (b) 20% Damage severity, (c) 10% Damage severity and (d) 5% Damage severity.	73
4.8	Laplacian (L_i) signatures for damage locations (a) 550mm and (b) 900mm.	74
4.9	Difference function (δi) plot for damage locations (a) 550mm and (b) 900mm.	74
4.10	Multiple damage case results showing (a) Laplacian (L_i) and (b) Difference function (δi).	75
5.1	Aluminium beam with high severity damage instrumented with sensor and actuator PZT patches.	83
5.2	Difference between healthy vs damaged frequencies.	84
5.3	δi curve calculated fitting 2nd to 6th order polynomial curves to CMS for experimental (a) Mode 1 (b) Mode 2 and (c) Mode 3.	85
5.4	R-Sq and S values for fitting 2nd to 6th order polynomial curves to CMS for experimental (a) Mode 1 (b) Mode 2 and (c) Mode 3.	86
5.5	R-Sq and S values of non-linear functions curves for experimental (a) Mode 1 (b) Mode 2 and (c) Mode 3.	87
5.6	Fitting non-linear functions curves (Sine vs Gauss Amp) to experimental (a) Mode 1 (b) Mode 2 and (c) Mode 3.	88
5.7	R-Sq and S values of linear vs non-linear functions curves for experimental (a) Mode 1 (b) Mode 2 and (c) Mode 3.	89
5.8	(a) Finite element model of aluminium beam with damage/cracks location; (b) Generated mesh of aluminium beam for modal analysis.	90
5.9	Numerical simulation results showing displacement mode shape one to three for both: (a) High damage severity (i.e. damage volume 120 mm ³) (b) Low damage severity (i.e. damage volume 0.08 mm ³).	93

FIGURE	CAPTION	PAGE NO.
5.10	Numerical simulation results showing CMS using Laplacian (Li) for: (a) High damage severity (i.e. damage volume 120 mm^3) (b) Low damage severity (i.e. damage volume 0.08 mm^3).	93
5.11	δi curve comparing different order linear polynomial curves and non linear functions for numerical simulation mode shapes having high damage severity (a) Mode 1 (c) Mode 2 (e) Mode 3 and low damage severity (b) Mode 1 (d) Mode 2 (f) Mode 3.	95
5.12	R-Sq and S values for fitting different order polynomial curves to CMS for numerical simulation mode shapes having high damage severity (a) Mode 1 (c) Mode 2 (e) Mode 3 and low damage severity (b) Mode 1 (d) Mode 2 (f) Mode 3.	96
5.13	R-Sq and S values of non-linear functions curves for numerical simulation mode shapes having high damage severity (a) Mode 1 (c) Mode 2 (e) Mode 3 and low damage severity (b) Mode 1 (d) Mode 2 (f) Mode 3.	97
5.14	R-Sq and S values of linear vs non-linear functions curves for first three numerical simulation mode shapes having high damage severity (a) Mode 1, (c) Mode 2, (e) Mode 3 and low damage severity (b) Mode 1, (d) Mode 2, (f) Mode 3.	97
6.1	Baseline-Free integrated approach for SHM.	102
6.2	Generation of S_O or A_O mode: (a) “in-phase” (b) “out-of-phase” excitation of PZTs X and Y simultaneously (Kim et al., 2011).	104
6.3	Six measured signals (a) V_{XX} to V_{AY} and three decomposed signals (b) $Z_S(t)$, $Z_A(t)$ and $Z_M(t)$ (Kim et al., 2011).	104
6.4	Aluminium beam specimen used for simulation.	108
6.5	Model of the section of the aluminium plate used for simulation.	108
6.6	PZT patch axes orientation considered while modelling (Moharana, 2013).	109
6.7	Impedance signals (resistance part): (a), (c) and (e) indicate healthy beam and (b), (d) and (f) indicate damage beam impedance signals V_{XX}/V_{YY} , V_{SX}/V_{SY} and V_{AX}/V_{AY} , respectively.	112

FIGURE	CAPTION	PAGE NO.
6.8	Decomposed individual impedance signals $\tilde{Z}_S$, $\tilde{Z}_A$ and $\tilde{Z}_M$ (resistance part) in numerical simulation : (a), (c) and (e) for healthy and (b), (d) and (f) for damaged beam, respectively.	113
6.9	Numerical simulation results comparing MC_{rms} and E_{rms} (resistance part) for (a) Healthy and (b) Damaged beam.	114
6.10	Numerical simulation results comparing resistance and reactance beam signatures for (a) MC_{rms} (Healthy) (b) MC_{rms} (Damaged) (c) E_{rms} (Healthy) (d) E_{rms} (Damaged)	114
6.11	Average amplitude value comparison between MC_{rms} (a) Healthy (b) Damaged beam and E_{rms} (c) Healthy (d) Damaged beam.	115
6.12	Experimental set-up.	117
6.13	Aluminium beam used in experimental investigations showing damage (a) case I and (b) case II.	117
6.14	Generation of symmetric (S_O) and anti-symmetric (A_O) wave signal using LCR by connecting PZT bottom edge electrode film to low current and potential (L_{CUR} & L_{POT}) and top electrode film to high current and potential (H_{CUR} & H_{POT}).	118
6.15	Healthy beam experimental outcomes from PZT patches: (a) Symmetric; S_O (Resistance), (b) Symmetric; S_O (Reactance), (c) Anti-symmetric; A_O (Resistance) and (d) Anti-symmetric; A_O (Reactance).	119
6.16	Impedance signals (resistance part): (a), (c) and (e) indicate healthy beam and (b), (d) and (f) indicate damage beam impedance signals V_{XX}/V_{YY} , V_{SX}/V_{SY} and V_{AX}/V_{AY} , for case1 respectively.	120
6.17	Decomposed individual impedance signals (resistance part) $\tilde{Z}_S$, $\tilde{Z}_A$ and $\tilde{Z}_M$, respectively, of healthy beam: (a), (c) and (e) and damaged beam: (b), (d) and (f) in experiment for case 1.	121
6.18	Experimental investigation results comparing MC_{rms} and E_{rms} (resistance part) (a) Healthy (b) Damaged beam.	122

LIST OF TABLES

TABLE	CAPTION	PAGE NO.
1.1	Classification of damage detection. (Rytter, 1993)	4
2.1	Comparison between NDE and SHM.	22
2.2	Local NDE techniques and their sensitivities. (Bhalla, 2004)	23
3.1	Comparison of natural frequencies of mode shapes obtained using hammer and PZT-patch excitations before and after damage.	52
4.1	Properties of simply-supported steel beam used for numerical investigations.	65
4.2	Modal frequencies and displacement of damaged aluminium beam.	67
4.3	Natural frequencies of damaged and undamaged structure.	68
5.1	Percentage change values of R-Sq and SE between linear vs non-linear functions curves for experimental (a) Mode 1 (b) Mode 2 and (c) Mode 3.	88
5.2	Properties of Aluminium beam simulation model.	91
5.3	Comparison of natural frequencies of mode shapes between theoretical and simulation values (before and after inducing damage).	92
6.1	PIC 151 piezoelectric properties. (Moharana, 2013)	109
6.2	E_{rms} values for reconstructing six impedance signals for healthy and two damage cases.	123

LIST OF SYMBOLS

A	Area in Eq. (5.4) and amplitude in Eq. (5.5) of the fitted curve respectively.
A_0	Anti-Symmetric.
B	Susceptance.
c	Global damping.
d	Depth of the beam.
d_{31}	Piezoelectric strain coefficient.
$\hat{d}$	PZT patch distance from the neutral axes.
D_3	Electric displacement over the PZT patch.
E	Modulus of elasticity.
E_{rms}	Reconstruction Error RMS.
f_n	Natural frequency of a beam.
$F(t)$	Force function.
$F(\omega)$	Nodal forces.
G	Conductance.
g	Gravitational acceleration.
$\hat{h}$	Length of elements in simulation.
h	Thickness of PZT patch.
I	Second moment of the cross-sectional area.
I'	Current in PZT patch.
k	Wave number.
K	Global stiffness.
k	PZT constant.
K_n	Constant where 'n' refers to the mode of vibration.
l	Half length of PZT patch.
$\mathcal{L}_i$	Laplacian function.
M	Bending moment at a section.
m	Global mass.
MC_{rms}	RMS (root mean square) of mode conversion.
n	Number of bends in the curve.
Q	Charge in PZT patch.

R	Resistance.
s_t	Strain at the top of the beam.
s_b	Strain at the bottom of the beam.
S_1	Strain in PZT patch in direction '1'.
S_0	Symmetric
T_1	Axial stress in direction '1'.
U	Displacement.
$\dot{u}$	Velocity.
$\ddot{u}$	Acceleration.
V	Potential difference across PZT patch terminals having h -thickness.
V_{in}	Input voltage supplied to the PZT.
w	Width of PZT patch.
ω	Angular frequency.
w	Width in Eq. (5.4) and period in Eq. (5.5) of the fitted curve respectively.
X	Reactance.
$x(\omega)$	Nodal degrees of freedom.
x_C	Center in Eq. (5.4) and phase shift in Eq. (5.5) of the fitted curve respectively.
y_o	Offset of the fitted curve.
$\bar{Y}$	Electro-mechanical admittance.
$\overline{Y^E}$	Complex Young's modulus of the PZT patch at constant electric field.
Y_i	Physical displacement /deformation of the node i.e. i in the defined mode shape.
$Y_{electrical}$	Electrical impedance.
Z_a	Actuator impedance.
Z_s	Mechanical impedance.
$Z_{electrical}$	Electrical impedance.
$\overline{\epsilon_{33}^T}$	Complex electric permittivity of the PZT material.
δ	Dielectric loss factor.

η	Mechanical loss factor of the PZT material.
δ	Dielectric loss factor of the PZT material.
$\emptyset$	Curvature of a beam at a particular position.
$\emptyset_i$	Curvature in the intact beam at location i .
$\emptyset_i^*$	Curvature in damaged beam at the location i .
$\Delta\emptyset_i$	Change in curvature at location i .
δ_i	Difference function.
ε	Surface strain of PZT patch.
v_i	Nodal displacement at <i>the</i> i^{th} node in simulation.
w_e	Starting angular frequencies.
w_s	Ending angular frequencies.
$\{\varphi_r\}$ and $\{\varphi_s\}$.	Modal vectors.

LIST OF ACRONYMS

CMS	Curvature Mode Shape
COMAC	Coordinate Modal Assurance Criterion
EM	Electro-Mechanical
EMA	Experimental Modal Analysis
EMI	Electro-Mechanical Impedance
FD	Fractal Dimension
FE	Finite Element
FFT	Fast-Fourier Transform
FRF	Frequency Response Functions
GFD	Generalized fractal Dimension
GSM	Gapped Smoothing Method
GW	Guided Wave
LCR	Inductance Capacitance Resist
MAC	Modal Assurance Criterion
MDLAC	Multiple damage Location Assurance Criterion
MEMS	Micro-Electro Mechanical Systems
MFC	Macro Fiber Composite
NDE	Non-Destructive Evaluation
PVDF	Polyvinylidene Fluoride
PZT	Piezoelectric Lead Zirconate
RMS	Root Mean Square
R-Sq	R-Squared for Regression Ana
SHM	Structure Health Monitoring
SOC	Social Overhead Capital
SS	Sum of Squares
S	Standard Error of the Regr
TRA	Time Reversal Acoustics
TRLW	Time Reversed Lamb Wave
WTC	Wavelet Transform Coefficient