

PIEZO-SENSOR BASED 3D STRAIN MODAL ANALYSIS APPROACH FOR STRUCTURAL HEALTH MONITORING

DATTAR SINGH AULAKH



DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

MARCH 2024

PIEZO-SENSOR BASED 3D STRAIN MODAL ANALYSIS APPROACH FOR STRUCTURAL HEALTH MONITORING

by

DATTAR SINGH AULAKH

Department of Civil Engineering

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MARCH 2024

*Dedicated to my family, teachers and friends, for their
support and guidance*

Certificate

This is to certify that the thesis entitled “**PIEZO-SENSOR BASED 3D STRAIN MODAL ANALYSIS APPROACH FOR STRUCTURAL HEALTH MONITORING**”, submitted by **Dattar Singh Aulakh** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Department of Civil Engineering, is a record of the original, bona fide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge.

New Delhi
March 2024

Prof. Suresh Bhalla
Professor
Department of Civil Engineering
Indian Institute of Technology Delhi

Acknowledgements

I want to begin by expressing my sincere and deepest gratitude to my mentor and advisor, **Dr. Suresh Bhalla**, who supported me throughout my journey as a research scholar. His unwavering support and inspiring ideas have served as a significant source of encouragement for me. His creative thinking and insightful criticism have been really helpful to me in this job. I will benefit from the ethics and discipline she taught me throughout my academic career. A sincere thank you to him for providing me with such flexibility to create my work plan and for always being there to assist, offer criticism, and provide important mentorship. Additionally, his spiritual mentoring has fostered my soul and mind to stay on the right path.

A very particular thank you to **Dr. Prateek Negi**, my senior who assisted me through every stage of my doctoral journey. He helped me develop the abilities to conduct my thinking experiments. I am grateful to my seniors **Mr. Sumit Balgavhar** and **Mrs. Jayalakshmi Raju**, for their guidance and support in my research journey.

If not for wonderful juniors like **Shipra Prakash** and **Ravi Shankar** who contributed with their efforts in the experimental and investigational work in the laboratory, working there would not have been so enjoyable.

I'm also grateful to my friends **Gurpinder Singh** and **Saba Rahman** for helping me with my experiments and for talking with me about my doctoral programme, and for converting all of my tea breaks into brainstorming sessions.

A particular thanks goes out to **Mr. Lal Singh** and **Mr. Ashok Lunia** (Smart Structures and dynamics laboratory) for their encouragement and interest in my work. I owe a huge debt of gratitude to **Mr. Himanshu Kashyap** (Smart Structures and dynamics laboratory) for his selfless assistance in making my experiments a reality. This document acknowledges the level of collaboration provided by everyone who contributed, either directly or indirectly, to the accomplishment of this work.

Of course, I must also express my gratitude to IIT Delhi, particularly the Civil Engineering Department, for welcoming me and giving me with all the facilities I

needed for my study, including a library, grants, and laboratories. I would never forget this location as a cosy nest that not only housed me throughout my time here but also offered a supportive setting for the development of my research ideas. My time on this campus will undoubtedly go down in my life as a remarkable one.

I want to express my love and gratitude towards my wife **Mrs. Jeevanpreet Kaur**, who herself being a research scholar, pushed me to give my best to this degree. She has been the strength and motivation in the highs and lows of my life.

Finally, I want to express my gratitude to my parents, **Mrs. Jaswinder Kaur** and **Mr. Gurender Singh Aulakh**, for everything in my life and for guiding me through my life. They have blessed, encouraged, and supported me in all I have accomplished. I sincerely appreciate everything you have done for me, so thank you everyone.

Dattar Singh Aulakh

Abstract

Vibration-based health monitoring of the structures has been well established and routinely implemented for structures. Any changes in modal parameters, which are functions of mass, stiffness and damping of the structure, reflect any perturbations in these parameters. Strain-based modal parameters are well-known to exhibit superior sensitivity to displacement-based modal parameters for damage monitoring, especially incipient damage. However, strain, being the second derivative of displacement, dissipates faster than displacement. Hence it is challenging to capture the dynamic strain response of the structure rich in information about structural behaviour. Piezo sensors have been established as extremely sensitive sensors for damage detection and location by the electro-mechanical impedance (EMI) technique. However, the application of the piezo sensors, albeit having edge over accelerometers in terms of cost, has been severely limited to the identification of first few bending modes in small, lightweight structures for SHM. Thus, it becomes imperative to develop an effective and low-cost structural health monitoring (SHM) approach based on dynamic strain signals acquired by piezo sensors. Towards this objective, this doctoral research investigates and evaluates the ceramic lead-zirconate-titanate (PZT) piezoelectric patches for structural identification and health monitoring of structures under different practical scenarios.

The study evaluates commercial PZT patches for modal testing and damage identification of small-scale structures to actual real-life structures. PZT patches are first investigated for structural identification and damage monitoring of 2D beams and plates by different types of modes, evaluating them against the industry standard accelerometers. PZT patch based strain modal identification and damage monitoring is performed based on bending and complex torsion modes for monitoring of different levels of damage resulting from the loosening of bolts. PZT patches are found to capture the dynamic strain response and modal parameters effectively. Strain-based modal parameters are observed to demonstrate enhanced sensitivity than the corresponding displacement-based modal parameters utilizing accelerometers for damage monitoring.

This study further extends the investigation of piezo sensor based modal structural identification to complex 3D structures. This has been conceptualized by adopting a scaled-down model of a pedestrian footover bridge, excited under different artificial excitations based on the shaker and impact hammer. Structural identification is performed under impact hammer and shaker based sweep and random white noise excitations. PZT patches based strain modal parameters are found to exhibit an excellent correlation to the corresponding displacement modal parameters under all the adopted artificial excitation scenarios.

Finally, the PZT patches are evaluated for their efficacy in structural identification under weak ambient excitations based on operational conditions. This is warranted as well-controlled artificial excitations are infeasible on real-life structures owing to exorbitant expenses and hassles in implementation. In this doctoral research this has been achieved by the application of ambient pedestrian motion based weak ambient excitations in different feasible patterns on the interior lane, and the exterior lane and staggered all over a scaled-down model of a real-life pedestrian bridge. The PZT patches are observed to capture the dynamic strain response with sufficient information about structural behaviour under weak pedestrian motion based excitations. Strain-based modal parameters are observed to be in good agreement with corresponding displacement-based modal parameters under all the adopted patterns of pedestrian motions, with staggered pedestrian motions found best among all the patterns for activation of modes.

PZT patches are also evaluated for sensitivity towards structural damage by modal testing under the staggered pattern of pedestrian motions. Artificial damage depicting member stiffness loss is inflicted on the scaled-down model of the pedestrian bridge at four different locations in two different intensities in the form of a vertical cut. Modal flexibility based curvature and Coordinate modal assurance criteria (CoMAC) indices are adopted as damage-sensitive features and an outlier analysis is performed for damage localization. PZT patch based strain modal parameters are observed to exhibit enhanced sensitivity than the corresponding displacement modal parameters towards incipient damage scenarios.

For field validation of the proposed approach, a real-life pedestrian footover bridge of span of 15 m is adopted. The applicability and issues in the adoption of PZT patches for dynamic strain measurement and structural identification under

pedestrian traffic on the bridge are investigated. Strain modal parameters are successfully extracted even under weak ambient excitations with excellent correlation to corresponding displacement modal parameters. Thus, piezo sensors are established as effective sensors for strain-based vibration monitoring of structures under operating conditions based weak ambient excitations.

In conclusion, the application of piezo sensors for dynamic strain-based modal analysis, including complex 3D modes, structural identification and health monitoring, is the original aspect and contribution of this doctoral research. Piezo sensors are established as effective sensors for dynamic strain measurement and structural identification in real-life structures under operational conditions based weak ambient excitations with performance having equivalent or high superiority to expensive accelerometers.

सार

संरचनाओं की कंपन-आधारित स्वास्थ्य निगरानी अच्छी तरह से स्थापित की गई है और संरचनाओं के लिए नियमित रूप से कार्यान्वित की गई है। मोडल मापदंडों में कोई भी परिवर्तन, जो संरचना के द्रव्यमान, कठोरता और भिगोना के कार्य हैं, इन मापदंडों में किसी भी गड़बड़ी को दर्शाते हैं। तनाव-आधारित मोडल पैरामीटर क्षति की निगरानी, विशेष रूप से प्रारंभिक क्षति के लिए विस्थापन-आधारित मोडल पैरामीटर के प्रति बेहतर संवेदनशीलता प्रदर्शित करने के लिए जाने जाते हैं। हालाँकि, तनाव, विस्थापन का दूसरा व्युत्पन्न होने के कारण, विस्थापन की तुलना में तेजी से नष्ट हो जाता है। इसलिए संरचनात्मक व्यवहार के बारे में जानकारी से भरपूर संरचना की गतिशील तनाव प्रतिक्रिया को पकड़ना चुनौतीपूर्ण है। इलेक्ट्रो-मैकेनिकल प्रतिबाधा (ईएमआई) तकनीक द्वारा क्षति का पता लगाने और स्थान के लिए पीजो सेंसर को बेहद संवेदनशील सेंसर के रूप में स्थापित किया गया है। हालाँकि, पीजो सेंसर का अनुप्रयोग, लागत के मामले में एक्सेलेरोमीटर पर बढ़त होने के बावजूद, एसएचएम के लिए छोटे, हल्के संरचनाओं में पहले कुछ झुकने वाले मोड की पहचान तक गंभीर रूप से सीमित कर दिया गया है। इस प्रकार, पीजो सेंसर द्वारा प्राप्त गतिशील तनाव संकेतों के आधार पर एक प्रभावी और कम लागत वाली संरचनात्मक स्वास्थ्य निगरानी (एसएचएम) दृष्टिकोण विकसित करना अनिवार्य हो जाता है। इस उद्देश्य की प्राप्ति के लिए, यह डॉक्टरेट अनुसंधान विभिन्न व्यावहारिक परिदृश्यों के तहत संरचनाओं की संरचनात्मक पहचान और स्वास्थ्य निगरानी के लिए सिरैमिक लेड-जिरकोनेट-टाइटनेट (पीजेडटी) पीजोइलेक्ट्रिक पैच की जांच और मूल्यांकन करता है।

अध्ययन मॉडल परीक्षण और क्षति के लिए वाणिज्यिक पीजेडटी पैच का मूल्यांकन करता है। वास्तविक वास्तविक जीवन संरचनाओं के लिए छोटे पैमाने की संरचनाओं की पहचान। पीजेडटी पैच की सबसे पहले विभिन्न प्रकार के मोड द्वारा 2डी बीम और प्लेटों की संरचनात्मक पहचान और क्षति की निगरानी के लिए जांच की जाती है, उद्योग मानक एक्सेलेरोमीटर के मुकाबले उनका मूल्यांकन किया जाता है। पीजेडटी पैच आधारित स्ट्रेन मोडल पहचान और क्षति की निगरानी बोल्ट के ढीले होने के परिणामस्वरूप होने वाली क्षति के विभिन्न स्तरों की निगरानी के लिए झुकने और जटिल मरोड़ मोड के आधार पर की जाती है। पीजेडटी पैच गतिशील तनाव प्रतिक्रिया और मोडल मापदंडों को प्रभावी ढंग से पकड़ने के लिए पाए जाते हैं। क्षति की निगरानी के लिए एक्सेलेरोमीटर का उपयोग करते हुए संबंधित विस्थापन-आधारित मोडल मापदंडों की तुलना में बढ़ी हुई संवेदनशीलता प्रदर्शित करने के लिए तनाव-आधारित मोडल पैरामीटर देखे जाते हैं।

यह अध्ययन पीजो सेंसर आधारित मोडल संरचनात्मक पहचान की जांच को जटिल 3डी संरचनाओं तक विस्तारित करता है। शेकर और प्रभाव हथौड़ा के आधार पर विभिन्न कृत्रिम उत्तेजनाओं के तहत उत्साहित पैदल यात्री फुटओवर ब्रिज के स्केल-डाउन मॉडल को अपनाकर इसकी संकल्पना की गई है। संरचनात्मक पहचान प्रभाव हथौड़ा और शेकर आधारित स्वीप और यादृच्छिक सफेद शोर उत्तेजना के तहत की जाती है। पीजेडटी पैच आधारित स्ट्रेन मोडल पैरामीटर सभी अपनाए गए कृत्रिम उत्तेजना परिदृश्यों के तहत संबंधित विस्थापन मोडल पैरामीटर के साथ उत्कृष्ट सहसंबंध प्रदर्शित करते पाए गए हैं।

अंत में, परिचालन स्थितियों के आधार पर कमजोर परिवेश उत्तेजनाओं के तहत संरचनात्मक पहचान में उनकी प्रभावकारिता के लिए पीजेडटी पैच का मूल्यांकन किया जाता है। यह आवश्यक है क्योंकि कार्यान्वयन में अत्यधिक खर्चों और परेशानियों के कारण वास्तविक जीवन संरचनाओं पर अच्छी तरह से नियंत्रित कृत्रिम उत्तेजनाएं संभव नहीं हैं। इस सैद्धांतिक अनुसंधान में इसे आंतरिक लेन और बाहरी लेन पर अलग-अलग व्यवहार्य पैटर्न में परिवेशीय पैदल यात्री गति आधारित कमजोर परिवेश उत्तेजनाओं के अनुप्रयोग द्वारा प्राप्त किया गया है और एक वास्तविक जीवन पैदल यात्री पुल के स्केल-डाउन मॉडल पर कंपित किया गया है। पीजेडटी पैच को कमजोर पैदल यात्री गति आधारित उत्तेजनाओं के तहत संरचनात्मक व्यवहार के बारे में पर्याप्त जानकारी के साथ गतिशील तनाव प्रतिक्रिया को पकड़ने के लिए देखा जाता है। पैदल यात्री गति के सभी अपनाए गए पैटर्न के तहत तनाव-आधारित मोडल पैरामीटर संबंधित विस्थापन-आधारित मोडल पैरामीटर के साथ अच्छे समझौते में पाए जाते हैं, मोड के सक्रियण के लिए सभी पैटर्न के बीच कंपित पैदल यात्री गति को सर्वोत्तम पाया जाता है।

पैदल चलने वालों की गति के क्रमबद्ध पैटर्न के तहत मॉडल परीक्षण द्वारा संरचनात्मक क्षति के प्रति संवेदनशीलता के लिए पीजेडटी पैच का भी मूल्यांकन किया जाता है। सदस्य की कठोरता के नुकसान को दर्शाने वाली कृत्रिम क्षति, ऊर्ध्वाधर कट के रूप में दो अलग-अलग तीव्रता में चार अलग-अलग स्थानों पर पैदल यात्री पुल के स्केल-डाउन मॉडल पर पहुंचाई गई है। मोडल लचीलापन आधारित वक्रता और कोऑर्डिनेट मोडल एशोरेंस मानदंड (सीओएमएसी) सूचकांकों को क्षति-संवेदनशील विशेषताओं के रूप में अपनाया जाता है और क्षति स्थानीयकरण के लिए एक बाहरी विश्लेषण किया जाता है। पीजेडटी पैच आधारित स्ट्रेन मोडल पैरामीटर प्रारंभिक क्षति परिदृश्यों के प्रति संबंधित विस्थापन मोडल पैरामीटर की तुलना में बढ़ी हुई संवेदनशीलता प्रदर्शित करने के लिए देखे गए हैं।

प्रस्तावित दृष्टिकोण के क्षेत्र सत्यापन के लिए, 15 मीटर के वास्तविक जीवन वाले पैदल यात्री फुटओवर ब्रिज को अपनाया गया है। पुल पर पैदल यात्री यातायात के तहत गतिशील तनाव माप और संरचनात्मक पहचान के लिए पीजेडटी पैच को अपनाने में प्रयोज्यता और मुद्दों की जांच की जाती है। संबंधित विस्थापन मोडल मापदंडों के साथ उत्कृष्ट सहसंबंध के साथ कमजोर परिवेश उत्तेजनाओं के तहत भी तनाव मोडल पैरामीटर सफलतापूर्वक निकाले जाते हैं। इस प्रकार, पीजो सेंसर को कमजोर परिवेशीय उत्तेजनाओं के आधार पर परिचालन स्थितियों के तहत संरचनाओं की तनाव-आधारित कंपन निगरानी के लिए प्रभावी सेंसर के रूप में स्थापित किया गया है।

निष्कर्ष में, जटिल 3डी मोड, संरचनात्मक पहचान और स्वास्थ्य निगरानी सहित गतिशील तनाव-आधारित मोडल विश्लेषण के लिए पीजो सेंसर का अनुप्रयोग, इस डॉक्टरेट अनुसंधान का मूल पहलू और योगदान है। महंगे एक्सेलेरोमीटर के बराबर या उच्च श्रेष्ठता वाले प्रदर्शन के साथ कमजोर परिवेश उत्तेजनाओं के आधार पर परिचालन स्थितियों के तहत वास्तविक जीवन संरचनाओं में गतिशील तनाव माप और संरचनात्मक पहचान के लिए पीजो सेंसर प्रभावी सेंसर के रूप में स्थापित किए गए हैं।

Contents

Certificate	i
Acknowledgements	ii
Abstract	iv
Contents	vii
List of Figures	xi
List of Tables	xvii
Acronyms	xix
Symbols	xxiii
1 INTRODUCTION	1
1.1 BACKGROUND AND MOTIVATION	2
1.2 STRUCTURAL HEALTH MONITORING	3
1.3 VIBRATION BASED MONITORING	8
1.3.1 MODAL ANALYSIS	10
1.4 SPATIAL AND MODAL DOMAIN	12
1.5 STRAIN MODAL ANALYSIS	13
1.5.1 PIEZOELECTRIC SENSORS	15
1.6 RESEARCH OBJECTIVES AND SCOPE	19
1.7 ORGANIZATION OF THESIS	20
2 VIBRATION-BASED SHM: STATE OF THE ART	23
2.1 VIBRATION BASED SHM	23
2.2 EXCITATION SOURCES IN MODAL ANALYSIS	26
2.2.1 EXPERIMENTAL MODAL ANALYSIS	26
2.2.2 OPERATIONAL MODAL ANALYSIS	29

2.3	IDENTIFICATION TECHNIQUES	30
2.3.1	TIME DOMAIN BASED IDENTIFICATION TECHNIQUES	31
2.3.1.1	Poly reference least square complex eigenvalue (p-LSCE)	31
2.3.1.2	Stochastic Subspace Identification (SSI)	33
2.3.2	FREQUENCY DOMAIN BASED IDENTIFICATION TECHNIQUES	36
2.3.2.1	Peak picking (PP)	36
2.3.2.2	Enhanced frequency domain decomposition (EFDD)	36
2.3.2.3	Poly-reference least square complex frequency (p-LSCF)	37
2.3.3	OTHER LESS POPULAR IDENTIFICATION TECHNIQUES	40
2.4	DAMAGE SENSITIVE FEATURES	40
2.4.1	FREQUENCY	41
2.4.2	DAMPING RATIO	43
2.4.3	MODE SHAPES	44
2.4.4	MODAL STRAIN ENERGY	47
2.4.5	MODAL FLEXIBILITY	49
2.5	SENSING TECHNOLOGIES FOR FIELD MODAL ANALYSIS	53
2.5.1	DISPLACEMENT BASED MODAL TESTING (DMT)	54
2.5.1.1	Working principle of accelerometer	54
2.5.1.2	Piezoresistive accelerometer	55
2.5.1.3	Piezoelectric accelerometer	56
2.5.1.4	Capacitive MEMS accelerometer	56
2.5.1.5	Integrated Electronic-Piezoelectric Accelerometers	56
2.5.2	STRAIN BASED MODAL TESTING (SMT)	58
2.5.2.1	Strain gauge	58
2.5.2.2	Fibre Bragg Grating optic sensor	60
2.5.2.3	Piezoelectric strain sensor	61
2.6	CRITICAL LITERATURE REVIEW: STRAIN MODAL ANALYSIS BASED SHM	65
2.7	RESEARCH OBJECTIVES AND SCOPE	67
3	STRAIN BASED EXPERIMENTAL MODAL IDENTIFICATION: LAB BENCHMARK STUDY	69
3.1	INTRODUCTION	69
3.2	EXPERIMENTAL STUDY ON STEEL BEAM	70
3.2.1	EXPERIMENTAL DETAILS	70
3.2.2	MODAL PARAMETER IDENTIFICATION	73
3.2.3	NUMERICAL MODAL ANALYSIS	77
3.3	EXPERIMENTAL STUDY ON STEEL PLATE	80
3.3.1	DAMAGE INDICATORS	82

3.3.2	NUMERICAL MODAL ANALYSIS	85
3.3.3	MODAL PARAMETERS BASED DAMAGE MONITORING	87
3.4	CONCLUING REMARKS	101
4	STRAIN BASED EXPERIMENTAL MODAL IDENTIFICATION: SHAKER BASED EXCITATION	105
4.1	INTRODUCTION	105
4.2	SCALED DOWN MODEL OF FOOTOVER BRIDGE FOR MODAL TESTING	106
4.3	NUMERICAL MODAL ANALYSIS	108
4.4	EXPERIMENTAL DETAILS	110
4.4.1	SENSOR INSTRUMENTATION	110
4.4.2	EXCITATION SETUP	112
4.4.3	STRUCTURAL IDENTIFICATION ALGORITHMS	114
4.5	RESULTS AND DISCUSSIONS	114
4.5.1	RAW TIME DOMAIN RESPONSE	115
4.5.2	MODAL FREQUENCY	115
4.5.3	DAMPING RATIO	124
4.5.4	MODE SHAPES	126
4.6	CONCLUDING REMARKS	132
5	STRAIN BASED OMA OF 3D STRUCTURES USING PEDESTRIAN MOTIONS	135
5.1	INTRODUCTION	135
5.2	EXPERIMENTAL DETAILS	136
5.2.1	SENSOR INSTRUMENTATION AND EXCITATION SETUP	137
5.2.2	MODAL PARAMETER IDENTIFICATION	139
5.3	RESULTS AND DISCUSSION	140
5.3.1	TIME DOMAIN RESPONSE SIGNALS AND PDFS	140
5.3.2	MODAL FREQUENCIES	141
5.3.2.1	Stabalization diagrams	141
5.3.2.2	Mode indicator functions	145
5.3.2.3	Modal phase collinearity	148
5.3.3	DAMPING RATIOS	149
5.3.4	MODE SHAPES	151
5.4	CONCLUDING REMARKS	158
6	DAMAGE ASSESSMENT USING STRAIN BASED OMA USING PEDESTRIAN MOTION	161
6.1	INTRODUCTION	161
6.2	EXPERIMENTAL DETAILS	162

6.2.1	EXCITATION SOURCE AND SENSOR INSTRUMENTATION	162
6.2.2	DAMAGE SCENARIOS	165
6.2.3	DAMAGE SENSITIVE FEATURES	166
6.2.3.1	Co-ordinate modal assurance criteria	167
6.2.3.2	Proportional flexibility matrix based curvature as DSF	168
6.2.4	OUTLIER ANALYSIS	170
6.3	MODAL PARAMETERS OF HEALTHY STATE	173
6.4	DAMAGE IDENTIFICATION AND LOCALIZATION	179
6.5	CONCLUDING REMARKS	193
7	STRAIN BASED OMA: APPLICATION ON REAL-LIFE FOOTOVER BRIDGE	195
7.1	INTRODUCTION	195
7.2	EXPERIMENTAL SETUP	196
7.2.1	SENSOR INSTRUMENTATION AND MEASUREMENT DETAILS	196
7.2.1.1	Preliminary modal analysis by single sensor	198
7.3	STRUCTURAL IDENTIFICATION TECHNIQUES	203
7.4	MODAL PARAMETERS OF BRIDGE	203
7.4.1	PSDs AND STABILIZATION DIAGRAMS	203
7.4.2	MODAL FREQUENCY	204
7.4.3	MODE SHAPES	205
7.4.4	DAMPING RATIOS	209
7.5	CONCLUDING REMARKS	210
8	CONCLUSIONS, LIMITATIONS AND FUTURE RECOMMENDATIONS	213
8.1	INTRODUCTION	213
8.2	RESEARCH CONCLUSIONS AND CONTRIBUTIONS	214
8.3	LIMITATIONS OF PIEZO SENSORS FOR VIBRATION BASED SHM	217
8.4	FUTURE RECOMMENDATIONS	218
	References	221
	References	221
	List of Publications	259
	Biography	261

List of Figures

1.1	Damage and collapse of various structures	4
1.2	Flow chart of typical SHM process	6
1.3	Classification of SHM techniques	7
1.4	Sensor layout in Signature bridge, India (Furtner et al., 2013)	10
1.5	(a) Direct effect (b) Indirect effect of a piezoelectric sensor	16
1.6	(a) Typical square PZT patch (b) coordinate axis of PZT patch Ceramic PI (2021)	17
1.7	Flow chart of schematics of thesis	21
2.1	Mode shapes representation of a beam (Avitabile, 2017)	28
2.2	Temperature-dependent modes: (a) Seolmun Bridge; (b) Gajwa Bridge.(Cho and Cho, 2022)	42
2.3	Artificial damage: (a) sketch, (b) photograph of the half cut, (c) photograph of the full cut, (d) photograph of the recovery. (Chang and Kim, 2016)	45
2.4	(a) CoMAC-based damage in Warren truss bridge (b) Magnified view (Chang and Kim, 2016)	46
2.5	The lab offshore platform model in the experiment: (a) physical model; (b) FE model (Wang and Xu, 2018)	48
2.6	Various modal strain energy based approach for damage monitoring by (a) SDI (b) MSEC (c) MSED (d) CMSE (Wang and Xu, 2018)	49
2.7	Steel frame structure used for the modal flexibility based damage monitoring(Bernagozzi et al., 2020)	51
2.8	Damage identification with modal flexibility based approach (a) existing UL method; (b) proposed UL + T method (Bernagozzi et al., 2020)	52
2.9	Operational layout of a piezoelectric accelerometer	55
2.10	Instrumentation of aeroplane wing with ESGs, FBGs and accelerometer for modal testing (Marques Dos Santos and Peeters, 2016)	61
2.11	Experimental using piezometric sensors for (a) EMA (Piana et al., 2016) (b) OMA (Neu et al., 2017)	64

3.1	Experimental setup for modal testing of beam (a) Data acquisition hardware (b) Steel beam in free-free beam	71
3.2	(a) Front side of beam (b) Rear of beam (c) Cross-section view of bonded pair of PZT patches (d) Sensor placement on beam with grid markings	72
3.3	Time record plots: (a) PZT 14 (b) PZT 27 (c) ACC 42 (d) ACC 47 .	74
3.4	Average FRF plots for all sensors	75
3.5	Mode shape acquired for PZT 14	76
3.6	MAC values for mode shapes between (a) PZT 14 and ACC 47 (b) PZT 14 and ACC 42 (c) PZT 27 and ACC 42 (d) PZT 27 and ACC 47	77
3.7	Finite element model of the beam in free-free condition	78
3.8	MAC value plots for numerical displacement mode shapes (a) PZT 14 (b) PZT27 (c) ACC 42 (d) ACC 47	80
3.9	Experimental setup for modal testing of plate	82
3.10	Damage location in meshed plate grid and sensor placement	82
3.11	A schematic representation of plate	84
3.12	Meshed model of supported plate	86
3.13	MAC values for numerical mode shapes with mode shapes from (a) accelerometer (b) PZT patch	87
3.14	Average FRF plots for all damage scenarios from piezo sensors	88
3.15	Average FRF plots for all damage scenarios from accelerometer	89
3.16	Mode shapes for the pristine state of the plate (a) Mode 1: first bending mode (b) Mode 2: first torsional mode (c) Mode 3: second torsional mode (d) Mode 4: second bending mode (e) Mode 5: third bending mode	92
3.17	DMAC values for damage scenarios using piezo sensor	93
3.18	DMAC values for damage scenarios using accelerometer	93
3.19	CoMAC values for bending and torsional modes from the accelerometer	95
3.20	CoMAC values for bending and torsional modes from piezo sensor . .	96
3.21	MSE values for bending and torsional modes from the accelerometer .	98
3.22	MSE values for bending and torsional modes from piezoelectric sensor	99
4.1	Panchsheel pedestrian foot over bridge	107
4.2	Scaled-down model of frame structure of Panchsheel bridge	108
4.3	Numerical wireframe model of the deck slab frame structure	109
4.4	Numerical mode shapes	111
4.5	Skeleton model with actual nodes and reduced nodes	112
4.6	Shaker-based mechanism for excitation	113
4.7	Time-domain response from (a) Piezo sensors (b) Accelerometers and probability distribution function from (a) Piezo sensors (b) Accelerometers	116

4.8	Average FRFs and crosspower spectrum under (a) IH (b) SR (c) SS excitations	117
4.9	p-LSCE Stabilization charts for piezo sensors based modal testing by IH excitations	117
4.10	p-LSCE Stabilization charts for piezo sensors based modal testing by SR excitations	118
4.11	p-LSCE Stabilization charts for piezo sensors based modal testing by SS excitations	118
4.12	p-LSCF Stabilization charts for accelerometers based modal testing by IH excitations	119
4.13	p-LSCF Stabilization charts for accelerometers based modal testing by SR excitations	119
4.14	p-LSCF Stabilization charts for accelerometers based modal testing by SS excitations	120
4.15	Mode identification function values for different excitations from (a) Piezo sensors (b) Accelerometers (Please refer Table 4.2 and Figure 4.4)	123
4.16	Coefficient of variation from modal frequencies from all types of excitations (Please refer Table 4.2 and Figure 4.4)	123
4.17	Damping ratios from (a) piezo sensors (b) accelerometers under different excitations (Please refer Table 4.2 and Figure 4.4)	125
4.18	Coefficient of variation from damping ratios from all types of excitations (Please refer Table 4.2 and Figure 4.4)	125
4.19	Strain mode shapes from piezo sensors based IH extraction (Please refer Table 4.2 and Figure 4.4)	127
4.20	MAC value histograms for numerical modes with IH-based modes from (a) piezo sensors (b) accelerometers (Please refer Table 4.2 and Figure 4.4)	128
4.21	Piezo sensors based auto MAC values between the modes shapes under IH and (a) SR (b) SS based excitations (Please refer Table 4.2 and Figure 4.4)	129
4.22	Accelerometers based auto MAC values between the modes shapes under IH and (a) SR (b) SS based excitations (Please refer Table 4.2 and Figure 4.4)	129
4.23	MAC value deviation plot between the auto MAC values (Please refer Table 4.2 and Figure 4.4)	130
4.24	Accelerometers based auto MAC values between the modes shapes under IH and (a) SR (b) SS based excitations (Please refer Table 4.2 and Figure 4.4)	131
5.1	Scaled-down model of the pedestrian foot over bridge	136
5.2	Visual representation of centric, eccentric and staggered pedestrian motions	138

5.3	Centric pedestrian motion by walking on the central longitudinal beam	138
5.4	(a) Time domain response (a) Probability distribution function for sensor location 11 under staggered pedestrian motions	141
5.5	Stabilization chart for centric pedestrian motion based excitations from the accelerometers	142
5.6	Stabilization chart for eccentric pedestrian motion based excitations from the accelerometers	143
5.7	Stabilization chart for staggered pedestrian motion based excitations from the accelerometers	143
5.8	Stabilization chart for centric pedestrian motion based excitations from the piezosensors	144
5.9	Stabilization chart for eccentric pedestrian motion based excitations from the piezosensors	144
5.10	Stabilization chart for staggered pedestrian motion based excitations from the piezosensors	145
5.11	Mode indicator functions plot for (a) Piezo sensor (b) Accelerometer (Please also refer Table 5.1)	147
5.12	Modal phase collinearity plots for (a) Piezo sensor (b) Accelerometer (Please also refer Table 5.1)	149
5.13	Damping ratio plot for (a) Piezo sensors (b) Accelerometer (Please also refer Table 5.1)	151
5.14	Piezo sensor based auto MAC value plots for mode shapes between the excitations from impact hammer and pedestrian motions based on (a) Centric motions (b) Eccentric motions (c) Staggered motions (Please also refer Table 5.1)	153
5.15	Accelerometer based auto MAC value plots for mode shapes between the excitations from impact hammer and (a) Centric motions (b) Eccentric motions (c) Staggered motions(Please also refer Table 5.1)	154
5.16	Auto MAC value deviation plot for MAC values under different excitations from piezo sensor with respect to accelerometers (Please also refer Table 5.1)	155
5.17	Cross MAC value plots for mode shapes from the accelerometer and piezo sensors for (a) Centric motions (b) Eccentric motions (c) Staggered motions (Please also refer Table 5.1)	158
6.1	Sensor instrumentation and damage locations	164
6.2	Flow chart for proposed damage detection by (a) impact hammer (EMA)(b) pedestrian motions (OMA)	167
6.3	Pedestrian motion based excitation based (a) time domain response (b) probability density functions	174
6.4	Pedestrian motion based stabilization charts for piezo sensors	175
6.5	Pedestrian motion based stabilization charts for accelerometers	175

6.6	Accelerometers and piezo sensor based plots for (a) Natural frequency (b) Damping ratios	176
6.7	Strain mode shapes under pedestrian motions	177
6.8	MAC values between the displacement and strain mode shapes	178
6.9	Box plots for modal frequency variation for pedestrian motion form (a) accelerometers (b) piezo sensors	180
6.10	Box plots for modal damping ratio variation for pedestrian motion from (a) accelerometers (b) piezo sensors	181
6.11	Norm analysis of modal flexibility matrices estimated from (a) impact hammer (b) pedestrian motions	182
6.12	Variation in modal flexibility based deflections incipient intensity for (a) DS1 (b) DS2 (c) DS3 (d) DS4	183
6.13	Variation in modal flexibility based deflections in severe intensity for (a) DS5 (b) DS6 (c) DS7 (d) DS8	184
6.14	Curvature based outlier analysis for damage states with incipient intensity for (a) DS1 (b) DS2 (c) DS3 (d) DS4	186
6.15	Curvature based outlier analysis for damage states with severe intensity for (a) DS5 (b) DS6 (c) DS7 (d) DS8	188
6.16	Comac based outlier analysis for damage states with incipient intensity for (a) DS1 (b) DS2 (c) DS3 (d) DS4	190
6.17	Comac based outlier analysis for damage states with severe intensity for (a) DS5 (b) DS6 (c) DS7 (d) DS8	192
7.1	Sensor instrumentation in the one span of footover bridge	197
7.2	Footover bridge with (a) pedestrian traffic based excitations (b) data acquisition system	198
7.3	(a) measured response (b) probability distribution functions from response by sensor location 2	199
7.4	PSD plots from single (a) accelerometer (b) piezo disc buzzer	200
7.5	Stabalization diagrams from single (a) accelerometer (b) piezo disc buzzer	200
7.6	PSD plot and Stabilization diagram from measurement run 1	204
7.7	Strain mode shapes of footover bridge under pedestrian traffic	206
7.8	MAC plots between the mode shapes from the EFDD and SSI for strain response from (a) measurement run 1 (b) measurement run 2 (c) measurement run 3	207
7.9	MAC plots between EFDD based mode shapes from measurement run 1 and (a) measurement run 2 (b) measurement run 3	208
7.10	MAC plots between SSI based mode shapes from measurement run 1 and (a) measurement run 2 (b) measurement run 3	208

List of Tables

1.1	Physical properties of PZT patch of grade PIC 151 (Ceramic PI, 2021)	19
3.1	Natural frequencies of the five modes of the beam (Hz)	74
3.2	Damping ratios of the five modes of the beam	75
3.3	Material properties considered in numerical model	78
3.4	Convergence study for the finite element model	78
3.5	Comparison of numerical and experimental vibration frequencies	79
3.6	Material properties of the numerical model	86
3.7	Experimental and numerical modal frequencies for pristine state	87
3.8	Vibrational frequencies for all damage states (Hz)	88
3.9	Damping ratios for damage states from Piezo sensors	90
3.10	Damping ratios for damage states from accelerometer	90
4.1	Dimensions of real-life pedestrian foot-over bridge and scaled-down model	108
4.2	Modal frequencies (Hz) from the piezo sensors and accelerometers under different excitations	121
5.1	Modal frequencies (Hz) extracted by p-LSCE technique (Please also refer Table 4.2)	146
6.1	Instrumentation details for different setups	164
6.2	Measurement specifications for modal testing	164
6.3	Progressive damage states adopted for monitoring	166
6.4	Progressive damage states adopted for monitoring	173
7.1	Modal frequencies from piezo disc buzzer and accelerometer	201
7.2	Damping ratios from piezo disc buzzer and accelerometer	202
7.3	Strain based modal frequencies from all measurement runs with mean and standard deviation	205
7.4	Strain based damping ratios from all measurement runs with mean and standard deviation	210

Acronyms

ACC	A cceleration
ADMS	A cceleration based D isplacement M ode S hape
ARMA	A uto R egressive M oving A verage
CoMAC	C ordinate M odal A ssurance C riteria
CoV	C oefficient V ariation
CMIF	C omplex M ode I ndicator F unction
CSI	C oMAC based S everity I ndex
DC	D irect C urrent
DMAC	D ifferential M odal A ssurance C riteria
DMT	D isplacement M odal T esting D ecomposition
DSF	D amage S ensitive F eature
EFDD	E nhanced F requency D omain D ecomposition
EMA	E xperimental M odal A nalysis
EMI	E lectro-mechanical I mpedance
EVD	E igen V alue D ecomposition
FBG	F iber B ragg G rating
FDD	F requency D omain D ecomposition
FFT	F ast F ourier T ransform
FRC	F iber R einforced C omposites
FRF	F requency R esponse F unction
IDFT	I nverse D iscrete F ourier T ransform
IH	I mpact H ammer
IRF	I mpulse R esponse F unctions
ITD	I brahim T ime D omain
MAC	M odal A ssurance C riteria
MCM	M ass C hange M ethod

MDOF	M ultiple D egree O f F reedom
MEMS	M icro E lectro M echanical S ystem
MFC	M acro F iber C omposite
MFM	M odal F lexibility M ethod
MIF	cceleration based D isplacement M ode S hape
MIMO	M ultiple I nput M ultiple O utput
ML	M achine L earning
MPC	M odal P hase C ollinearity
MSC	M ode S hape C urvature
MSE	M odal S train E nergy
MSECR	M odal S train E nergy C hange R atio
MSED	M odal S train E nergy D ecomposition
MSI	M SE based S everity I ndex
NDMS	N umerical D isplacement M ode S hape
NDT	N on D estructive T esting
NExT	N atural E xcitation D ecomposition
NMD	N ormalized M odal D ifference
OMA	O peratioanl M odal A nalysis
PBIL	P ositive B ending I nspection L oad
PDF	M ode I ndicator F unction
PFM	P roportional F lexibility M atrix
p-LSCE	polyreference L east S quare C omplex E xponential
p-LSCF	polyreference L east S quare C omplex F requency
PP	P eak P icking
PSD	P ower S pectral D ensity
PSIL	P ositive S hear I nspection L oad
PVDF	P olyvinylidene F luoride
PZT	L ead Z irconate T itanate
rCoMAC	rresidual textbfCordinate M odal A ssurance C riteria
RC	R einforced C omposites
SDI	S tubbs D amage I ndex
SDOF	S ingle D egree O f F reedom
SDMS	S train based D isplacement M ode S hape
SHM	S tructural H ealth M onitoring
SIMO	S ingle I nput M ultiple O utput

SISO	S ingle I ntput S ingle O utput
SMT	S train M odal T esting
SR	S haker based R andom
SS	S haker based S weep
SSI	S tochastic S ubspace I dentification
SVD	S ingular V alue D ecomposition

Symbols

a	Distance between the degree of freedom
A	State transition matrix
A_{jk}^r	Modal constant of mode r
C	Damping of structure
C_s	State Output matrix
$CoMAC_q$	CoMAC value at q_{th} degree of freedom
d_{31}	Piezoelectric strain coefficient for axis 1-3
d	Piezoelectric strain coefficient
D	Stiffness of the 2D plate
D_e	Electric displacement vector
D_3	Electric displacement vector along axis 3
E	Electric field
E_3	Electric field along axis 3
f_{min}	fundamental vibrating frequency of structure
F	Flexibility matrix
$F_{r,ij}$	Fractional modal strain energy in reference state
$F_{r,ij}^*$	Fractional modal strain energy in damage state
$F(t)$	Force applied on structure
H	Frequency response function
G	Next state output covariance matrix
G_{xx}	Input power spectral matrix
G_{yy}	Output power spectral matrix
h	Thickness of piezoelectric sensor
h_{jk}	Frequency response functions
h_{jk}^ε	Strain frequency response functions
H	Hankel matrix

I_{jk}	Impulse response functions
K	Stiffness of structure
l	Observation vector
m	mean vector of observations
m_d	Mahalanobis distance
m_d^{cr}	Critical mahalanobis distance
m_{ddc}	m_d for displacement flexibility based curvature for impact hammer
m_{ddo}	m_d for displacement flexibility based curvature for pedestrian motions
m_{sdc}	m_d for strain flexibility based curvature for impact hammer
m_{sdo}	m_d for strain flexibility based curvature for pedestrian motions
m_{dce}	m_d for displacement mode shapes based rCoMAC for impact hammer
m_{dco}	m_d for displacement mode shapes based rCoMAC for pedestrian motions
m_{sce}	m_d for strain mode shapes based rCoMAC for impact hammer
m_{sco}	m_d for strain mode shapes based rCoMAC for pedestrian motions
MAC_q	MAC value at q_{th} degree of freedom
n	Data samples
N	Degrees of freedom
O_i	Observability matrix
p	Load vector
R	Covariance
r	Proportionality factor
s	Modal participation factor
S	Second-order strain tensor
S_s	Eigenvalue matrix of singular value decomposition
S_1	Second-order strain tensor along axis 1
Γ_i	Controllability matrix
T_i	Toeplitz matrix
T	Second-order stress tensor
T_1	Second-order stress tensor along axis 1
T_{min}	Minimum duration of response measurement
$u(t)$	Displacement response of structure
$\dot{u}$	Velocity response of structure
$\ddot{u}$	Acceleration response of structure
u_i	Response of structure at i_{th} degree of freedom
U	Modal strain energy

U_r	Modal strain energy of 2D plate in mode r in reference state
U_s	Orthogonal matrix from singular value decomposition
U_r^*	Modal strain energy of 2D plate in mode r in damage state
$U_{r,ij}$	Modal strain energy or an element situated between nodes i, j, i + 1 and j + 1 in reference state
$U_{r,ij}^*$	Modal strain energy or an element situated between nodes i, j, i + 1 and j + 1 in damage state
V_s	Orthogonal matrix from singular value decomposition
v_k	Measurement noise
V_p	Voltage generated by piezoelectric sensor
w	Transverse displacement
w_k	Process noise
x_k	State vector at k_{th} time instant
y_k	State vector at k_{th} time instant
$\overline{Y^E}$	Complex young's modulus of elasticity
Z_{ij}	Normalized modal strain energy damage index
ω	Frequency
ω_r	Modal frequency of mode r
ζ_r	Damping ratio of mode r
ϕ_r	Displacement Mode shape of mode r
$\overline{\phi}$	Mass normalized displacement mode shape
ε_x	Strain
ψ_x	Strain mode shape
ϵ_0	Permittivity of free space
$\overline{\epsilon^T}$	Complex electric permittivity
$\overline{\epsilon_{33}^T}$	Complex electric permittivity along axis 3
η	Mechanical loss factor
δ	Dielectric loss factor
λ_r	Eigenvalues of system
β_l	Auto regressive coefficients
α_r	denominator matrix polynomial coefficients
α_B	Thermal coefficients
ρ_r	numerator matrix polynomial coefficients
ζ_B	Thermos-optic coefficients
ϕ''	Mode shape curvature

Symbols

ϕ_h''	Mode shape curvature in healthy state
ϕ_d''	Mode shape curvature in damage state
$\delta\phi''$	Mode shape curvature difference
γ_q	Normalized CoMAC values
$\overline{CoMAC}_q$	Mean CoMAC values
σ_{yc}	Standard deviation of CoMAC values
μ	Poisson's ratio
β_{ij}	Modal strain energy based damage index
$\overline{\beta}_{ij}$	Mean modal strain energy based damage index
σ_{ys}	Standard deviation of modal strain energy damage index
λ_B	Bragg wavelength
p^{eff}	photo-elastic parameter