

MODELLING OF PIEZO-STRUCTURE ELASTODYNAMIC INTERACTION THROUGH BOND LAYER FOR ELECTRO- MECHANICAL IMPEDANCE TECHNIQUE

by

SUMEDHA MOHARANA

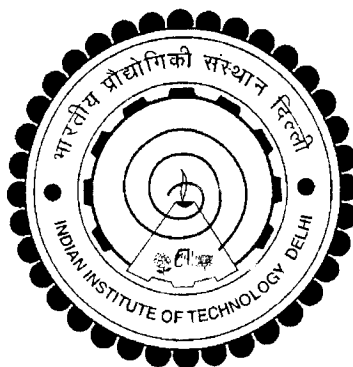
Department of Civil Engineering

Submitted

in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



Indian Institute of Technology Delhi

November 2012

I. I. T. DELHI.
LIBRARY
Acc. No...*TH.4327*.....

CERTIFICATE

This is to certify that the thesis entitled, “**MODELLING OF PIEZO-STRUCTURE ELASTODYNAMIC INTERACTION THROUGH BOND LAYER FOR ELECTRO-MECHANICAL IMPEDANCE TECHNIQUE**” submitted by **Ms. Sumedha Moharana** to Indian Institute of Technology Delhi, for the award of the degree of the **Doctor of Philosophy** is a record of bonafide research work carried out by her. She worked under my supervision for the submission of this thesis, which to the best of my knowledge, has reached the requisite standard.

The research reports and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.



Dr. Suresh Bhalla

Associate Professor

Department of Civil Engineering

Indian Institute of Technology, Delhi

New Delhi – 110016

INDIA

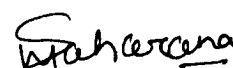
ACKNOWLEDGEMENTS

First and foremost, I would like to extend my sincere thanks and gratitude towards my supervisor, Dr Suresh Bhalla, for his continuous guidance, encouragement and strong support during the course of my Ph.D. research. It has been an honour to be associated with Dr. Suresh Bhalla whose suggestions and critical views have greatly helped me in this work. I am eternally grateful for his kindness, helpful guidance, and discussions. He truly exemplifies the role of advisors. I am forever grateful for his kindness and contributions, not only towards my research, but towards my professional growth as well.

I am grateful to my committee members of Prof K. G. Sharma, Dr. Swadesh De and Dr Vasant Matsagar, who provided their useful suggestions and advice regarding my research work. I thank my friends Sanjay and Usha, without them, things would have been very difficult. I am also thankful to my colleague, Vishalakshi, Naveet and Dinesh, for providing imminent helps to conduct the lab experiments.

My thanks are also due to all the Civil Engineering faculty and other staff members for their support and keenness in my work. I am extremely grateful to the staff of Smart Structures and Dynamics Laboratory (SSDL), departmental and central library for providing books, journals etc., which made this research work possible.

I express my special thanks to Mr Lal Singh, Mr Vinod, Mr Mansukh and other technicians, who provided their technical support generously during the lab work. Special thanks go to almighty God and my parent and sisters for their encouragement and love. Their support and kind encouragements provided the essential foundation to thrive and success.


Sumedha Moharana

ABSTRACT

As impedance transducers, the piezoelectric ceramic (PZT) patches have emerged as strong candidates for structural health monitoring (SHM) of structures in the recent years because of their small size and shape, cost-effectiveness and ease of installation. The research for structural identification and long-term monitoring has recently become an area of interest for a large number of academic and commercial laboratories. The associated techniques aim to enable structures and equipment monitor their own structural integrity while in operation, and shall be useful not only to improve reliability, but also to reduce maintenance and inspection costs.

This thesis is focused on the electro-mechanical impedance (EMI) technique for SHM. The basic principle behind this technique is to use high frequencies (typically >50 kHz) generated by surface-bonded PZT patch to detect changes in structural drive point impedance caused by internal/ surface cracks, loose connections, delaminations or any other type of damage. The resultant electro-mechanical interaction, which is characteristic of the particular structure, modulates the current flowing through the PZT patch. The modulation is a function of the mechanical interaction between the PZT patch and the structure over the considered frequency range. The resultant admittance signature, which acts like a frequency response function (FRF), is used to detect changes or damages occurring in the host structure.

The bond layer between the PZT patch and host structure plays a significant role in PZT-structure interaction in the EMI technique. To understand the mechanism of force transfer through the adhesive medium (which introduce shear lag effect) more precisely, various models have been proposed by researchers in the past. Some of those are based on static, dynamic, effective and simplified interaction through the bond layer. However, these models still lack

rigour in terms of considering all governing parameters, especially both shear and inertia terms simultaneously. Understanding shear mechanism phenomena of the adhesive layer is vital for enhanced applicability of the EMI technique.

The main objective of this research work is to model the shear lag phenomena (between PZT patch and host structure) analytically, achieving more accurate model. The previous analytical models have ignored the inertia term, which has been rigorously integrated in this research to arrive at a new refined shear lag model. The new model considers both shear lag and inertia effects simultaneously. The predictions of the new model are much better match with experimental observations as compared to the previous models. Various parametric studies have also been carried out to study the influence of the piezo and the structural properties on the admittance signatures.

The research is further extended by considering the inertia effect of the adhesive mass (so far neglected) in addition to that of the PZT patch. A continuum based admittance approach has been formulated where the “equivalent and effective impedance” terms are replaced by continuum displacement term developed at interfacial adhesive bond. This model considers the bond layer’s connection between the patch and structure throughout the sensor length, unlike the previous models which were restricted to boundary interactions. Parametric studies have followed to support the sustainability and suitability of proposed continuum approach. Finally, to enhance the efficiency of the proposed model in real life application on SHM and active control system, the study of electrical power consumption and energy efficiency has been carried out. Various energy conversion efficiency ratios have been obtained by evaluating the total energy used for mechanical response to the total energy supplied. In overall, the study shows significant influence of the bond layer on energy efficiency. A modified electro-mechanical

coupling coefficient has been derived from basic strain energy relationship taking care of the mechanical, dielectric and shear lag losses of piezo active control system.

In overall, it is hoped that the outcome of this research will be of significant help SHM based on EMI technique.

CONTENTS

CERTIFICATE.....	i
ACKNOWLEDGEMENTS	ii
ABSTRACT.....	iii
CONTENTS	vi
LIST OF FIGURES	ix
LIST OF TABLES	xvi
LIST OF SYMBOLS.....	xvii
LIST OF ABBREVIATIONS	xxiii
CHAPTER-1: INTRODUCTION	1
1.1 Research Background	1
1.2 Motivation.....	1
1.3 Smart Materials And Structures.....	3
1.4 Basics of EMI Technique	4
1.5 Shear Lag Effect.....	6
1.6 Power and Energy Consumption For Bonding Effect.....	7
1.7 Various SHM techniques: A comparison	9
1.8 Thesis Organization.....	10
CHAPTER-2:IMPEDANCE BASED MODELING OF PIEZO-STRUCTURE INTERACTION.....	12
2.1 Introduction	12
2.2 EMI Based Structural Health Monitoring	14
2.3 Piezo-Structure Interaction Modeling For EMI Technique.....	17
2.3.1 Static Approach	17
2.3.2 Impedance Approach	19
2.4 Inclusion of Shear Lag Effect In Impedance Based Models	29
2.5 Numerical Investigation of Shear Lag Effect of FE Piezo-Structure Interaction Model	35
2.6 Summary: Critical Points of Review.....	39
2.7 Gaps identified in previous research	40
2.7 Research Objectives	41

CHAPTER-3: COUPLED FIELD FINITE ELEMENT MODELLING AND SIMULATION OF SHEAR LAG EFFECT FOR EMI TECHNIQUE	42
3.1 Introduction	42
3.2 FE Modelling of PZT Transducers.....	43
3.3 Review of FE Modelling Using Coupled-Field Analysis	44
3.4 Theory of Coupled Piezoelectric Analysis	45
3.5 2D FE Modelling of Adhesively Bonded PZT Patch.....	52
3.6 3D FE Modelling of Adhesively Bonded PZT Patch	57
3.7.1 Parametric Study For Piezo-Structure Interaction	63
(a) Effect of Bond Length	63
(b) Effect of Shear Modulus	64
(c) Effect of Bond Layer Damping	65
3.8 Concluding Remarks	65
CHAPTER-4 : DEVELOPMENT OF SHEAR LAG MODEL	67
4.1 Introduction	67
4.2 Derivation of Proposed 1D Shear Lag Model.....	67
4.3 Extension of Refined Shear Lag Formulation to 2D.....	72
4.4 Comparison with Previous Models and Experiment.....	75
4.5 Effect of Inclusion of Adhesive Mass	83
4.6 Interfacial Stress and Strain Analysis for Coupled Phenomena	85
4.6.1 Shear Stress Profile Along Bond Layer	87
4.6.2 Effective Strain Profile Along Bond Layer	91
4.6.3 Variation Effective Axial Stress Along Adhesive Bond	93
4.7 Parametric Study of Adhesive Bond Layer Induced Admittance Signature	94
4.7.1 Effect of Bond Layer's Shear Modulus	94
4.7.2 Effect of Bond Layer Thickness.....	94
4.7.3 Influence of Damping bond layer	96
4.7.4 Effect of Sensor Length	96
4.7.5 Effect of Excitation Voltage.....	97
4.8 Concluding Remarks	98
CHAPTER-5 : EXTENSION TO CONTINUUM BASED SHEAR LAG MODEL.....	99
5.1 Introduction	99

5.2 Derivation of Admittance Signature using Continuum Approach.....	100
5.3 Experimental Verification	103
5.4 Parametric Study for Continuum Signature.....	108
5.5 Effect on Adhesive Mass on Continuum Based Admittance Signature.....	112
5.6 Conclusions	114
CHAPTER-6 : Bond Effect on Power And Energy Transduction Efficiency.....	115
6.1 Introduction.....	115
6.2 Electrical Impedance And Power Triangle.....	115
6.3 Power and Energy Flow in Piezo-Mechanical Interaction	118
6.4 Electrical Power Consumption in Piezo-Impedance Transducer.....	121
6.5 Energy Conversion Efficiency of Piezo-Active Mechanical System.....	128
6.6 Energy Conversion Efficiency Ratio For Bonding Influence On Piezo-Impedance System	130
6.7 Formulations for Modified Electro-Mechanical Coupling Coefficient.....	134
6.8 Concluding Remarks	137
CHAPTER-7: CONCLUSIONS AND RECOMENDATIONS	138
7.1 Introduction.....	138
7.2 Research originality and contributions.....	139
7.3 Research conclusions	140
7.4 Recommendations	142
REFERENCES	145
APPENDICES	157
AUTHOR'S PUBLICATION	167
BIODATA	169