TABLE OF CONTENTS

Chapter 1

Introduction 1

1.1 Background 1

1.2 Research Objectives 3

1.3 Research Contribution 4

1.4 Vibration based Non-Destructive Evaluation Techniques 5

1.5 Piezoelectric Impedance-Based Structural Health Monitoring 10

1.5.1 Electromechanical Principle 10

1.5.2 Related Previous Work 12

1.5.3 Impedance-based Structural Health Monitoring Technique Parameters… 13

1.5.3.1 Sensing Region 13

1.5.3.2 Frequency Range 14

1.5.3.3 Damage Assessment 15

1.5.4 Comparison with other Damage Identification Approaches 15

1.5.5 Summary 17

1.6 Dissertation organization 18

Chapter 2

Refinements of the Impedance-Based Structural Health Monitoring Technique: Part I. Compensating Effects of Temperature Changes 20

2.1 Introduction 20

2.2 Temperature Effects on Piezoelectric Materials 21

2.3 Temperature Effects on the Monitored Structures 23

2.4 The Compensation Procedure 31

2.5 Proof-of-Concept Applications 34

2.5.1 A Bolted Pipe Joint 34

        2.5.2 Abrasive Wear of Gears 37
        2.5.3 Delaminations of Composite Reinforced Patches 40
    2.6 Summary 43

Chapter 3

**Refinements of the Impedance-Based Structural Health Monitoring Technique:
Part II. Analyzing Effects of Boundary and Environmental Condition Changes** 45
    3.1 Introduction 45
    3.2 A ¼ scale Bridge Section 46
    3.3 A massive Cylinder Header 52
    3.4 Summary 60

Chapter 4

Extensions of the Impedance-Based Structural Health Monitoring Technique 61
    4.1 Extending technique to high temperature applications 61
        4.1.1 Introduction 61
        4.1.2 Experimental Setup 62
        4.1.3 Results and Analysis 64
        4.1.4 Summary 66
    4.2 Health Assessment of Pipeline Structures 67
        4.2.1 Introduction 67
        4.2.2 Experimental Setup 68
        4.2.3 Experimental Results 69
        4.2.4 Summary 74
    4.3 Summary 74

Chapter 5

A Quantitative Health Monitoring Approach using Impedance Sensors 76
    5.1 Introduction 76
    5.2 Wave Propagation Model 77

5.3 Damage Identification using Frequency Response Functions 79
5.4 Simulation Results 81
5.5 Experimental Results 84
5.6 Summary 91

Chapter 6

Impedance-Based Health Monitoring with Artificial Neural Networks 92
6.1 Introduction 92
6.2 Principle of Artificial Neural Networks 93
6.3 Damage Identification Scheme 95
6.4 Simulation Results 97
6.5 Proof-of-Concept Applications 101
    6.5.1 A quarter scale Bridge Section 101
    6.5.2 Analysis of a Space Truss Structure 104
6.6 Summary 110

Chapter 7

Conclusions and Recommendations 111
7.1 Conclusions 111
7.2 Recommendations 114

References 116

Vita 126

LIST OF FIGURES

Figure 1.1 1-D model used to represent a PZT-driven dynamic mechanical system. 11

Figure 2.1 For a free PZT PSI-5A, an increase in temperature leads to a small magnitude change in the real part of electrical impedance. 22

Figure 2.2 Predicted ratio of natural frequency of the steel beam shifting with temperature (reference temperature = 75 ºF) 26

Figure 2.3 Schematic of the experiment on temperature effects 27

Figure 2.4 FRF measurement of the carbon-steel beam with the temperature change........... 28

Figure 2.5 Real part of electrical admittance of the carbon-steel beam with the temperature change. 29

Figure 2.6 Real part of electrical impedance of the carbon-steel beam with the temperature change at high frequency range... 30

Figure 2.7 Compensated electrical impedance of the carbon-steel beam with the temperature change 33

Figure 2.8 Experimental setup of bolted pipe joint 35

Figure 2.9 Electrical impedance measurements with the temperature change in a bolted pipe joint: (a) uncompensated impedance for temperature variations, (b) compensated impedance for temperature variations...................... 36

Figure 2.10 The damage metric chart of uncompensated and compensated impedance compared against the reference impedance measured at 25 $^\circ C$ - Bolted pipe joint.. 37

Figure 2.11 Detection of abrasive wear in gears was investigated.. 38

Figure 2.12 Electrical impedance with the temperature change in gear: (a) uncompensated impedance, (b) compensated impedance.................................... 39

Figure 2.13 The damage metric chart of uncompensated and compensated impedance compared against the reference impedance measured at 25 $^\circ C$ - Gear... 40

Figure 2.14 Experimental setup for composite reinforced aluminum plate 41

Figure 2.15 Electrical impedance with the temperature change in composite

reinforced aluminum plate: (a) uncompensated impedance, (b) compensated impedance 42
Figure 2.16 The damage metric chart of uncompensated and compensated impedance compared against the reference impedance measured at 25 °C - composite reinforced aluminum plate 43
Figure 3.1 A ¼ scale steel bridge section. 47
Figure 3.2 Impedance (real) vs. Frequency plots of PZT 1: (a) uncompensated impedance, (b) compensated impedance 48
Figure 3.3 Impedance (real) vs. Frequency plots of PZT 1: (a) uncompensated impedance, (b) compensated impedance 49
Figure 3.4 Damage metric chart for PZTs. Comparison of metric values with induced damage 51
Figure 3.5 Impedance vs. Frequency plots for PZT 2 52
Figure 3.6 Three PZT actuator/sensors were used to find damage in the header section. 54
Figure 3.7 The variation in the real impedance measurements shows that vibration gives the largest change: (a) uncompensated impedance, (b) compensated impedance 55
Figure 3.8 The variation in the real impedance measurements shows that higher frequency ranges are more sensitive than the lower frequency range: (a) uncompensated impedance, (b) compensated impedance 56
Figure 3.9 The damage metric to identify the extent of damage that could be detected over the boundary condition changes in the header: (a) Frequency Range 44-45 kHz, (b) Frequency Range 147-150 kHz 58
Figure 3.10 The damage metric for the 44-45 kHz frequency range. Damage metric induced by 3 holes gives significant value over that produced by vibration 59
Figure 4.1 Bolted joint used in the high temperature experiment 62
Figure 4.2 The material Characteristics of Lithium Niobate used in the experiment. (Provided by Valpey-Fisher corporation) 63

Figure 4.3 The electrical impedance measurements at temperature 500 ℃: (a) Frequency Range of 100-115 kHz, (b) Frequency Range of 130-150 kHz 65
Figure 4.4 Damage metric chart over the different frequency range. Damage metrics are normalized against the value of damage... 66
Figure 4.5 A pipeline used in the experiment... 69
Figure 4.6 The electrical impedance measurements of PZTs at Junction D 70
Figure 4.7 Damage Metric Chart. Comparison of metric values with induced damage 70
Figure 4.8 The electrical impedance measurements of PZTs at Junction B.......................... 72
Figure 4.9 The electrical impedance measurements of PZTs at Junction G 72
Figure 4.10 Damage metric chart over the different locations 73
Figure 5.1 Free-Free bar with ten spectral elements.. 81
Figure 5.2 Response at u7 of free-free bar with noise added to the damaged response 82
Figure 5.3 DLV Chart. The 5th and 6th dofs correspond to the element five 83
Figure 5.4 Percent Change in α . 13% change in Element 5. 84
Figure 5.5 Experiement Setup 85
Figure 5.6 Impedance measurement of PZT 3 for both undamaged and damaged cases 86
Figure 5.7 Damage Metric charts. PZT3 and PZT4 shows significant change, which in turn indicates damage is between these two sensors....................................... 87
Figure 5.8 The response of u2 from both simulation and experiment 15% change in wave number (dashed) and undamaged curves (solid): (a) Experimental results, (b) Analytical results.. 90
Figure 5.9 The response of u4 from both simulation and experiment. 15% change in wave number (dashed) and undamaged curves (solid): (a) Experimental results, (b) Analytical results.. 91
Figure 6.1 Architecture of the neural network with one hidden layer.................................. 93
Figure 6.2 Diagram of the damage detection scheme.. 96
Figure 6.3 Undamaged and damage responses (30 % increase in wave number): (a)

element 1, (b) element 4 98
Figure 6.4 A ¼ scale steel bridge section 102
Figure 6.5 A space-bay structure with PZT bonded on balls 105
Figure 6.6 Impedance measurements of PZT D: (a) Undamaged and damaged 1 to 3, (b) Undamaged and damaged 4 to 6.. 106
Figure 6.7 Results obtained by analyzing signals of Test 7: (a) PZT D, (b) PZT G 108
Figure 6.8 Results obtained by analyzing signals of Test 8: (a) PZT D, (b) PZT G 109

LIST OF TABLES

Table 6.1 Results for the NN with one and two hidden layers.. 100
Table 6.2 Damage identified in the position 2 103
Table 6.3 Damage identified in the position 4 103