

# Table of Contents

Abstract .....	ii
Acknowledgements .....	iii
Table of Contents .....	iv
List of Figures .....	vii
List of Tables .....	ix

## Chapter 1

Introduction .....	1
1.1 Background .....	1
1.2 Research Objectives .....	3
1.3 Research Contributions .....	3
1.4 Literature Review and Technology Introduction .....	4
1.4.1 Vibration Based Non-Destructive Evaluation Techniques .....	4
1.4.2 Impedance-based Health Monitoring Technique .....	7
1.4.3 Self-Repairing Structures .....	11
1.4.4 Shape Memory Alloy Technology .....	14
1.5 Outline of Thesis .....	18

## Chapter 2

Low Cost Impedance Measurements .....	20
2.1 Introduction .....	20
2.2 Conventional Impedance Measurements .....	20
2.3 Alternative Impedance Measuring Circuits .....	23
2.4 Proof-of-Concept Experiments .....	26
2.4.1 Bolted Joint Experiment .....	26
2.4.2 Pipeline Experiment .....	29
2.4.3 Detecting Damage in a Composite Beam .....	32
2.5 Conclusions .....	34

## **Chapter 3**

Bolted Joint Diagnostics .....	36
3.1 Introduction .....	36
3.2 Literature Review .....	36
3.3 Investigation of Natural Frequency Variations with Changes in Torque ...	37
3.3.1 Modal Experiment .....	38
3.3.2 Impedance Experiment .....	38
3.3.3 Results .....	41
3.4 Characterization of Damping .....	42
3.4.1 Experimental Configuration .....	43
3.4.2 Analysis of Experimental Data .....	46
3.4.3 Mathematical Model .....	48
3.4.4 Experimental Results .....	51
3.4.5 Analytical Results .....	54
3.5 Conclusions .....	57

## **Chapter 4**

Adaptive Bolted Joints .....	59
4.1 Introduction .....	59
4.2 Heating Model .....	60
4.3 Resistive Heating Experiment .....	65
4.4 External Heater Experiment .....	72
4.5 Ring Sizing .....	77
4.6 Conclusions .....	79

## **Chapter 4**

Conclusion and Future Work .....	81
5.1 Conclusion .....	81
5.2 Future work .....	84

<b>References</b> .....	<b>85</b>
-------------------------	-----------

**Appendix A**

Mathematica Code for SMA Ring Heating Model ..... 91

**Vita** ..... 94

## List of Figures

Figure 1.1	1-D model representing a PZT-driven dynamic structural system .....	9
Figure 1.2	Atomic arrangements of alloys exhibiting the shape memory effect .....	15
Figure 1.3	Temperature hysteresis (from Raychem, Actuator Design) .....	16
Figure 1.4	Schematic showing superelasticity of SMA .....	17
Figure 1.5	The Frangibolt separation system .....	18
Figure 2.1	Self-sensing actuator circuit (rate of strain sensor).....	22
Figure 2.2	Circuit for approximating PZT impedance .....	23
Figure 2.3	Impedance approximating circuit with amplification .....	24
Figure 2.4	FFT Analyzer and current measuring circuit .....	25
Figure 2.5	Bolted beam schematic .....	27
Figure 2.6	Impedance method measurement comparison .....	27
Figure 2.7	Low cost response to simulated damage .....	28
Figure 2.8	Traditional response to simulated damage .....	29
Figure 2.9	Portion of pipeline structure .....	30
Figure 2.10	Close up of joint showing location of PZT's .....	30
Figure 2.11	Comparison of low cost to traditional method on pipeline structure .....	31
Figure 2.12	Damage metric for traditional and low cost impedance .....	32
Figure 2.13	Undamaged composite beam with PZT attached .....	33
Figure 2.14	Low-cost impedance box, SigLab Analyzer and PC .....	33
Figure 2.15	Damage at far end of beam .....	33
Figure 2.16	Damage at end near PZT .....	33
Figure 2.17	Impedance measurements with accumulating damage .....	34
Figure 3.1	Magnitude of FRF for varying torques .....	38
Figure 3.2	Example of impedance measurements and resulting transfer impedance .....	39
Figure 3.3	Impedance based and modal based response of joint at 40 ft-lbs .....	41
Figure 3.4	Natural frequency variation of modal data with torque level .....	42
Figure 3.5	Natural frequency variation of transfer impedance data with torque level ..	42
Figure 3.6	Schematics of beam specimens .....	43
Figure 3.7	Jointed beam schematic .....	43

Figure 3.8 Segmented beam geometry .....	44
Figure 3.9 Solid beam geometry .....	44
Figure 3.10 Beam instrumentation .....	45
Figure 3.11 Sample frequency response functions of jointed and solid beams .....	46
Figure 3.12 Nonlinear finite element model schematic .....	50
Figure 3.13 Typical response time history and its envelope for the jointed beam .....	51
Figure 3.14 Typical response time history and its envelope for the monolithic beam ..	52
Figure 3.15. Estimates of local linear damping factor for the monolithic beam .....	52
Figure 3.16 Estimates of local linear damping factor for the jointed beam .....	53
Figure 3.17 Computed velocity response of linear system, and its envelope .....	55
Figure 3.18 Computed velocity response of nonlinear system, and its envelope .....	55
Figure 3.19 Estimates of local linear damping factor for the linear beam model .....	56
Figure 3.20 Estimates of local linear damping factor for the nonlinear beam model ....	56
Figure 4.1 Schematic of SMA ring .....	62
Figure 4.2 Heating model of ring with no insulation .....	62
Figure 4.3 Heating model of ring with ceramic washers .....	64
Figure 4.4 Schematic of beam used in heating experiments .....	66
Figure 4.5 Self-healing by resistive heating configuration .....	66
Figure 4.6 Resistive heating experiment impedance from 2.8 kHz to 3.2 kHz .....	67
Figure 4.7 Resistive heating experiment impedance from 5 kHz to 7 kHz .....	68
Figure 4.8 Resistive heating experiment impedance from 10 kHz to 12 kHz .....	68
Figure 4.9. Resistive heating experiment impedance from 12.5 kHz to 15 kHz .....	70
Figure 4.10 Resistive heating experiment impedance from 15 kHz to 18 kHz .....	70
Figure 4.11 Resistive heating experiment impedance from 30 kHz to 35 kHz .....	71
Figure 4.12 Bolted joint with heater .....	73
Figure 4.13 External heater experiment impedance from 2.8 kHz to 3.2 kHz .....	74
Figure 4.14 External heater experiment impedance from 7 kHz to 12 kHz .....	75
Figure 4.15 External heater experiment impedance from 15 kHz to 18 kHz .....	76
Figure 4.16 Ring showing uneven actuation .....	76

## List of Tables

Table 3.1	Natural frequencies and damping ratio from analysis of modal data .....	40
Table 3.2	Natural frequencies and damping ratio from analysis of impedance data ....	40
Table 4.1	SMA ring properties .....	61
Table 4.2	Ceramic ring properties .....	63