

ADVANCED STRUCTURAL DAMAGE DETECTION: FROM THEORY TO ENGINEERING APPLICATIONS

Tadeusz Stepinski

AGH University of Science and Technology, Poland
and Uppsala University, Sweden

Tadeusz Uhl and Wieslaw Staszewski

AGH University of Science and Technology, Poland

WILEY

Contents

List of Contributors	xi
Preface	xiii
Acknowledgments	xvii
1 Introduction	1
1.1 Introduction	1
1.2 Structural Damage and Structural Damage Detection	2
1.3 SHM as an Evolutionary Step of NDT	4
1.4 Interdisciplinary Nature of SHM	5
1.5 Structure of SHM Systems	9
1.5.1 <i>Local SHM Methods</i>	9
1.5.2 <i>Global SHM Methods</i>	10
1.6 Aspects Related to SHM Systems Design	12
1.6.1 <i>Design Principles</i>	13
References	15
2 Numerical Simulation of Elastic Wave Propagation	17
2.1 Introduction	17
2.2 Modelling Methods	18
2.2.1 <i>Finite Difference Method</i>	19
2.2.2 <i>Finite Element Method</i>	20
2.2.3 <i>Spectral Element Method</i>	21
2.2.4 <i>Boundary Element Method</i>	23
2.2.5 <i>Finite Volume Method</i>	24
2.2.6 <i>Other Numerical Methods</i>	25
2.2.7 <i>Time Discretization</i>	27

2.3	Hybrid and Multiscale Modelling	29
2.4	The LISA Method	33
2.4.1	<i>GPU Implementation</i>	36
2.4.2	<i>Developed GPU-Based LISA Software Package</i>	37
2.4.3	<i>cuLISA3D Solver's Performance</i>	38
2.5	Coupling Scheme	39
2.6	Damage Modelling	47
2.7	Absorbing Boundary Conditions for Wave Propagation	48
2.8	Conclusions	50
	References	51
3	Model Assisted Probability of Detection in Structural Health Monitoring	57
3.1	Introduction	57
3.2	Probability of Detection	58
3.3	Theoretical Aspects of POD	59
3.3.1	<i>Hit/Miss Analysis</i>	59
3.3.2	<i>Signal Response Analysis</i>	61
3.3.3	<i>Confidence Bounds</i>	63
3.3.4	<i>Probability of False Alarm</i>	64
3.4	From POD to MAPOD	64
3.5	POD for SHM	65
3.6	MAPOD of an SHM System Considering Flaw Geometry Uncertainty	66
3.6.1	<i>SHM System</i>	66
3.6.2	<i>Simulation Framework</i>	67
3.6.3	<i>Reliability Assessment</i>	67
3.7	Conclusions	70
	References	71
4	Nonlinear Acoustics	73
4.1	Introduction	73
4.2	Theoretical Background	75
4.2.1	<i>Contact Acoustics Nonlinearity</i>	76
4.2.2	<i>Nonlinear Resonance</i>	79
4.2.3	<i>Frequency Mixing</i>	80
4.3	Damage Detection Methods and Applications	85
4.3.1	<i>Nonlinear Acoustics for Damage Detection</i>	87
4.4	Conclusions	103
	References	104
5	Piezocomposite Transducers for Guided Waves	109
5.1	Introduction	109
5.2	Piezoelectric Transducers for Guided Waves	110
5.2.1	<i>Piezoelectric Patches</i>	110
5.2.2	<i>Piezocomposite Based Transducers</i>	111
5.2.3	<i>Interdigital Transducers</i>	113

5.3	Novel Type of IDT-DS Based on MFC	118
5.4	Generation of Lamb Waves using Piezocomposite Transducers	120
5.4.1	<i>Numerical Simulations</i>	120
5.4.2	<i>Experimental Verification</i>	122
5.4.3	<i>Numerical and Experimental Results</i>	124
5.4.4	<i>Discussion</i>	129
5.5	Lamb Wave Sensing Characteristics of the IDT-DS4	131
5.5.1	<i>Numerical Simulations</i>	132
5.5.2	<i>Experimental Verification</i>	133
5.6	Conclusions	136
	Appendix	136
	References	137
6	Electromechanical Impedance Method	141
6.1	Introduction	141
6.2	Theoretical Background	142
6.2.1	<i>Definition of the Electromechanical Impedance</i>	143
6.2.2	<i>Measurement Techniques</i>	144
6.2.3	<i>Damage Detection Algorithms</i>	146
6.3	Numerical Simulations	147
6.3.1	<i>Modelling Electromechanical Impedance with the use of FEM</i>	147
6.3.2	<i>Uncertainty and Sensitivity Analyses</i>	150
6.3.3	<i>Discussion</i>	153
6.4	The Developed SHM System	155
6.5	Laboratory Tests	158
6.5.1	<i>Experiments Performed for Plate Structures</i>	159
6.5.2	<i>Condition Monitoring of a Pipeline Section</i>	161
6.5.3	<i>Discussion</i>	163
6.6	Verification of the Method on Aircraft Structures	165
6.6.1	<i>Monitoring of a Bolted Joint in the Main Undercarriage Bay</i>	165
6.6.2	<i>Monitoring of a Riveted Fuselage Panel</i>	168
6.6.3	<i>Discussion</i>	172
6.7	Conclusions	173
	References	174
7	Beamforming of Guided Waves	177
7.1	Introduction	177
7.2	Theory	179
7.2.1	<i>Imaging Using Synthetic Aperture</i>	179
7.2.2	<i>Effective Aperture Concept</i>	183
7.2.3	<i>Imaging Schemes</i>	185
7.2.4	<i>Self-Focusing Arrays</i>	187
7.3	Numerical Results	190
7.3.1	<i>Examples of Effective Aperture</i>	190
7.3.2	<i>Imaging Using Star-like Array</i>	192
7.3.3	<i>Numerical Verification of the DORT-CWT Method</i>	196

7.4	Experimental Results	199
7.4.1	<i>Experimental Setup</i>	199
7.4.2	<i>Experimental Evaluation of Sensing Array</i>	200
7.4.3	<i>Experimental Evaluation of Effective Aperture</i>	201
7.4.4	<i>Damage Imaging Using Synthetic Aperture</i>	203
7.4.5	<i>Experimental Validation of the DORT-CWT Method</i>	203
7.4.6	<i>Damage Imaging Using Self-Focused Transmitting Array</i>	206
7.5	Discussion	207
7.6	Conclusions	209
	References	210
8	Modal Filtering Techniques	213
8.1	Introduction	213
8.2	State of the Art	214
8.3	Formulation of the Method	219
8.4	Numerical Verification of the Method	222
8.4.1	<i>Models Used for Simulation</i>	223
8.4.2	<i>Testing Procedure</i>	224
8.4.3	<i>Results of Analyses</i>	226
8.4.4	<i>Model Based Probability of Detection</i>	230
8.5	Monitoring System Based on Modal Filtration	231
8.5.1	<i>Main Assumptions</i>	231
8.5.2	<i>Measuring Diagnostic Unit</i>	232
8.5.3	<i>Modal Analysis and Modal Filtration Software</i>	234
8.6	Laboratory Tests	235
8.6.1	<i>Programme of Tests</i>	235
8.6.2	<i>Results of Experiments</i>	237
8.6.3	<i>Probability of Detection Analysis</i>	239
8.7	Operational Tests	245
8.8	Summary	248
	References	248
9	Vibrothermography	251
9.1	Introduction	251
9.2	State of the Art in Thermographic Nondestructive Testing	252
9.3	Developed Vibrothermographic Test System	261
9.4	Virtual Testing	263
9.5	Laboratory Testing	269
9.6	Field Measurements	273
9.7	Summary and Conclusions	275
	References	275
10	Vision-Based Monitoring System	279
10.1	Introduction	279
10.2	State of the Art	281
10.3	Deflection Measurement by Means of Digital Image Correlation	282

10.4	Image Registration and Plane Rectification	284
10.5	Automatic Feature Detection and Matching	287
	<i>10.5.1 Deflection-Shaped Based Damage Detection and Localization</i>	289
10.6	Developed Software Tool	291
10.7	Numerical Investigation of the Method	291
	<i>10.7.1 Numerical Modelling of the Developed Vision Measurement System</i>	292
	<i>10.7.2 Uncertainty Investigation of the Method</i>	292
	<i>10.7.3 Model Based Probability of Damage Detection</i>	297
10.8	Laboratory Investigation of the Method	301
	<i>10.8.1 Tests of the Method on the Laboratory Setup</i>	303
	<i>10.8.2 The Probability of Detection of the Method in the Laboratory Investigation</i>	307
	<i>10.8.3 Investigation of the Developed Method's Accuracy</i>	309
10.9	Key Studies and Evaluation of the Method	314
	<i>10.9.1 Tram Viaduct Deflection Monitoring</i>	314
10.10	Conclusions	318
	References	318
	Index	321