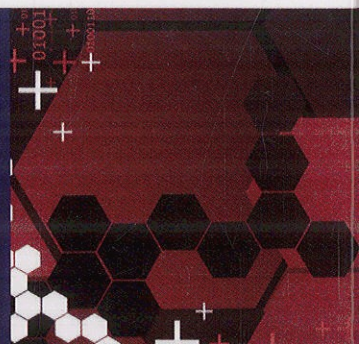


# Smart Technologies *for* Safety Engineering

EDITOR **JAN HOLNICKI-SZULC**

 **WILEY**



# Contents

|   |             |
|---|-------------|
| <b>Preface</b>  | <b>xi</b>   |
| <b>About the Authors</b>  | <b>xiii</b> |
| <b>Organization of the Book</b>                                       | <b>xvii</b> |
| <b>1 Introduction to Smart Technologies</b>                           | <b>1</b>    |
| <i>Jan Holnicki-Szulc, Jerzy Motylewski and Przemysław Kotakowski</i> |             |
| 1.1 Smart Technologies – 30 Years of History                          | 1           |
| 1.2 Smart-Tech Hardware Issues  | 3           |
| 1.2.1 Structural Health Monitoring                                    | 3           |
| 1.2.2 Adaptive Impact Absorption                                      | 6           |
| 1.3 Smart-Tech Software Issues  | 8           |
| References  | 9           |
| <b>2 The Virtual Distortion Method – A Versatile Reanalysis Tool</b>  | <b>11</b>   |
| <i>Przemysław Kotakowski, Marcin Wikto and Jan Holnicki-Szulc</i>     |             |
| 2.1 Introduction  | 11          |
| 2.2 Overview of Reanalysis Methods                                    | 12          |
| 2.3 Virtual Distortion Method – The Main Idea                         | 15          |
| 2.4 VDM in Structural Statics   | 16          |
| 2.4.1 Influence Matrix in Statics                                     | 16          |
| 2.4.2 Stiffness Remodeling in Statics                                 | 17          |
| 2.4.3 Plasticity in Statics   | 19          |
| 2.4.4 Example 1 in Statics  | 20          |
| 2.4.5 Example 2 in Statics  | 22          |
| 2.5 VDM in Structural Dynamics  | 23          |
| 2.5.1 Influence Matrices in Dynamics                                  | 23          |
| 2.5.2 Stiffness Remodeling in Dynamics                                | 24          |
| 2.5.3 Plasticity in Dynamics  | 26          |
| 2.5.4 Mass Remodeling in Dynamics                                     | 27          |
| 2.6 VDM-Based Sensitivity Analysis                                    | 29          |

|          |   |            |
|----------|---|------------|
| 2.7      | Versatility of VDM in System Modeling   | 29         |
| 2.8      | Recapitulation  | 30         |
| 2.8.1    | <i>General Remarks</i>  | 30         |
| 2.8.2    | <i>Applications of the VDM to Structures</i>  | 31         |
| 2.8.3    | <i>Applications of the VDM to Nonstructural Systems</i>   | 32         |
|          | References  | 33         |
| <b>3</b> | <b>VDM-Based Health Monitoring of Engineering Systems</b>   | <b>37</b>  |
|          | <i>Przemysław Kołakowski, Andrzej Świercz, Anita Orłowska, Marek Kokot and Jan Holnicki-Szulc</i>         |            |
| 3.1      | Introduction to Structural Health Monitoring  | 37         |
| 3.2      | Damage Identification in Skeletal Structures  | 39         |
| 3.2.1    | <i>Introduction</i>   | 39         |
| 3.2.2    | <i>Time Domain (VDM-T) versus Frequency Domain (VDM-F)</i>  | 39         |
| 3.2.3    | <i>Modifications in Beams</i>   | 41         |
| 3.2.4    | <i>Problem Formulation and Optimization Issues</i>  | 42         |
| 3.2.5    | <i>Numerical Algorithm</i>  | 44         |
| 3.2.6    | <i>Numerical Examples</i>   | 45         |
| 3.2.7    | <i>Experimental Verification</i>  | 48         |
| 3.2.8    | <i>Conclusions</i>  | 51         |
| 3.3      | Modeling and Identification of Delamination in Double-Layer Beams   | 52         |
| 3.3.1    | <i>Introduction</i>   | 52         |
| 3.3.2    | <i>Modeling of Delamination</i>   | 53         |
| 3.3.3    | <i>Identification of Delamination</i>   | 62         |
| 3.3.4    | <i>Conclusions</i>  | 67         |
| 3.4      | Leakage Identification in Water Networks  | 68         |
| 3.4.1    | <i>Introduction</i>   | 68         |
| 3.4.2    | <i>Modeling of Water Networks and Analogies to Truss Structures</i>                                       | 68         |
| 3.4.3    | <i>VDM-Based Simulation of Parameter Modification</i>   | 71         |
| 3.4.4    | <i>Leakage Identification</i>   | 76         |
| 3.4.5    | <i>Numerical Examples</i>   | 79         |
| 3.4.6    | <i>Conclusions</i>  | 84         |
| 3.5      | Damage Identification in Electrical Circuits  | 84         |
| 3.5.1    | <i>Introduction</i>   | 84         |
| 3.5.2    | <i>Modeling of Electrical Circuits and Analogies to Truss Structures</i>                                  | 85         |
| 3.5.3    | <i>VDM Formulation</i>  | 89         |
| 3.5.4    | <i>Defect Identification</i>  | 94         |
| 3.5.5    | <i>Numerical Example</i>  | 97         |
| 3.5.6    | <i>Conclusions</i>  | 99         |
|          | References  | 100        |
| <b>4</b> | <b>Dynamic Load Monitoring</b>  | <b>105</b> |
|          | <i>Łukasz Jankowski, Krzysztof Sekuła, Bartłomiej D. Błachowski, Marcin Wikło, and Jan Holnicki-Szulc</i> |            |
| 4.1      | Real-Time Dynamic Load Identification   | 105        |
| 4.1.1    | <i>Impact Load Characteristics</i>  | 106        |
| 4.1.2    | <i>Solution Map Approach</i>  | 107        |
| 4.1.3    | <i>Approach Based on Force and Acceleration</i>   | 107        |
| 4.1.4    | <i>Approaches Based on Conservation of Momentum</i>   | 108        |

|          |  |            |
|----------|--|------------|
| 4.1.5    | <i>Experimental Test Stand</i>   | 110        |
| 4.1.6    | <i>Experimental Verification</i>   | 113        |
| 4.1.7    | <i>Comparison of Approaches</i>  | 124        |
| 4.2      | <b>Observer Technique for On-Line Load Monitoring</b>  | 124        |
| 4.2.1    | <i>State-Space Representation of Mechanical Systems</i>  | 125        |
| 4.2.2    | <i>State Estimation and Observability</i>  | 125        |
| 4.2.3    | <i>Model-Based Input Estimation</i>  | 127        |
| 4.2.4    | <i>Unknown Input Observer</i>  | 127        |
| 4.2.5    | <i>Numerical Examples</i>  | 130        |
| 4.3      | <b>Off-Line Identification of Dynamic Loads</b>  | 132        |
| 4.3.1    | <i>Response to Dynamic Loading</i>   | 133        |
| 4.3.2    | <i>Load Reconstruction</i>   | 136        |
| 4.3.3    | <i>Optimum Sensor Location</i>   | 144        |
| 4.3.4    | <i>Numerical Example</i>   | 146        |
|          | <b>References</b>  | 150        |
| <b>5</b> | <b>Adaptive Impact Absorption</b>  | <b>153</b> |
|          | <i>Piotr K. Pawłowski, Grzegorz Mikułowski, Cezary Graczykowski,<br/>Marian Ostrowski, Łukasz Jankowski and Jan Holnicki-Szulc</i> |            |
| 5.1      | <b>Introduction</b>  | 153        |
| 5.2      | <b>Multifolding Materials and Structures</b>   | 155        |
| 5.2.1    | <i>Introduction</i>  | 155        |
| 5.2.2    | <i>The Multifolding Effect</i>   | 156        |
| 5.2.3    | <i>Basic Model of the MFM</i>  | 157        |
| 5.2.4    | <i>Experimental Results</i>  | 159        |
| 5.3      | <b>Structural Fuses for Smooth Reception of Repetitive Impact Loads</b>  | 160        |
| 5.3.1    | <i>Introductory Numerical Example</i>  | 161        |
| 5.3.2    | <i>Optimal Control</i>   | 162        |
| 5.3.3    | <i>Structural Recovery</i>   | 163        |
| 5.3.4    | <i>Numerical Example of Adaptation and Recovery</i>  | 164        |
| 5.4      | <b>Absorption of Repetitive, Exploitative Impact Loads in Adaptive<br/>Landing Gears</b>   | 166        |
| 5.4.1    | <i>The Concept of Adaptive Landing Gear</i>  | 166        |
| 5.4.2    | <i>Control System Issues</i>   | 167        |
| 5.4.3    | <i>Modeling of ALG</i>   | 169        |
| 5.4.4    | <i>Control Strategies</i>  | 174        |
| 5.4.5    | <i>Potential for Improvement</i>   | 181        |
| 5.4.6    | <i>Fast Control of an MRF-Based Shock Absorber</i>   | 184        |
| 5.5      | <b>Adaptive Inflatable Structures with Controlled Release of Pressure</b>  | 187        |
| 5.5.1    | <i>The Concept of Adaptive Inflatable Structures (AIS), Mathematical<br/>Modeling and Numerical Tools</i>                          | 187        |
| 5.5.2    | <i>Protection against Exploitative Impact Loads for Waterborne Transport</i>   | 192        |
| 5.5.3    | <i>Protective Barriers against an Emergency Crash for Road Transport</i>   | 199        |
| 5.5.4    | <i>Adaptive Airbag for Emergency Landing in Aeronautic Applications</i>  | 202        |
| 5.6      | <b>Adaptive Crash Energy Absorber</b>  | 203        |
| 5.6.1    | <i>Low-Velocity Impacts</i>  | 203        |
| 5.6.2    | <i>Energy Absorption by the Prismatic Thin-Walled Structure</i>  | 205        |
| 5.6.3    | <i>Use of Pyrotechnic Technology for the Crash Stiffness Reduction</i>   | 207        |
|          | <b>References</b>  | 211        |

|          |   |            |
|----------|---|------------|
| <b>6</b> | <b>VDM-Based Remodeling of Adaptive Structures Exposed to Impact Loads</b>          | <b>215</b> |
|          | <i>Marcin Wikło, Łukasz Jankowski, Małgorzata Mróz and Jan Holnicki-Szulc</i>       |            |
| 6.1      | Material Redistribution in Elastic Structures                                       | 217        |
| 6.1.1    | <i>VDM Formulation</i>  | 217        |
| 6.1.2    | <i>Sensitivity Analysis</i>   | 220        |
| 6.1.3    | <i>Numerical Testing Example</i>  | 221        |
| 6.2      | Remodeling of Elastoplastic Structures  | 223        |
| 6.2.1    | <i>VDM Formulation</i>  | 223        |
| 6.2.2    | <i>Sensitivity Analysis</i>   | 229        |
| 6.3      | Adaptive Structures with Active Elements  | 232        |
| 6.3.1    | <i>Stiffest Elastic Substructure</i>  | 234        |
| 6.3.2    | <i>Structural Fuses as Active Elements</i>  | 237        |
| 6.3.3    | <i>Comments</i>   | 240        |
| 6.4      | Remodeling of Damped Elastic Structures   | 241        |
| 6.4.1    | <i>Damping Model</i>  | 242        |
| 6.4.2    | <i>General VDM Formulation</i>  | 242        |
| 6.4.3    | <i>Specific Formulations and Sensitivity Analysis</i>                               | 244        |
|          | References  | 247        |
| <b>7</b> | <b>Adaptive Damping of Vibration by the Prestress Accumulation/Release Strategy</b> | <b>251</b> |
|          | <i>Arkadiusz Mróz, Anita Orłowska and Jan Holnicki-Szulc</i>                        |            |
| 7.1      | Introduction  | 251        |
| 7.2      | Mass–Spring System  | 252        |
| 7.2.1    | <i>The Concept</i>  | 252        |
| 7.2.2    | <i>Analytical Solution</i>  | 252        |
| 7.2.3    | <i>Case with Inertia of the Active Spring Considered</i>                            | 255        |
| 7.3      | Delamination of a Layered Beam  | 257        |
| 7.3.1    | <i>PAR Strategy for Layered Beams</i>   | 257        |
| 7.3.2    | <i>Numerical Example of a Simply Supported Beam</i>                                 | 258        |
| 7.3.3    | <i>PAR – the VDM Formulation</i>  | 260        |
| 7.4      | Experimental Verification   | 262        |
| 7.4.1    | <i>Experimental Set-up</i>  | 262        |
| 7.4.2    | <i>Control Procedure</i>  | 262        |
| 7.4.3    | <i>Results</i>  | 263        |
| 7.5      | Possible Applications   | 266        |
|          | References  | 266        |
| <b>8</b> | <b>Modeling and Analysis of Smart Technologies in Vibroacoustics</b>                | <b>269</b> |
|          | <i>Tomasz G. Zieliński</i>  |            |
| 8.1      | Introduction  | 269        |
| 8.1.1    | <i>Smart Hybrid Approach in Vibroacoustics</i>                                      | 269        |
| 8.1.2    | <i>A Concept of an Active Composite Noise Absorber</i>                              | 270        |
| 8.1.3    | <i>Physical Problems Involved and Relevant Theories</i>                             | 271        |
| 8.1.4    | <i>General Assumptions and Some Remarks on Notation</i>                             | 271        |
| 8.2      | Biot's Theory of Poroelasticity   | 272        |
| 8.2.1    | <i>Isotropic Poroelasticity and the Two Formulations</i>                            | 272        |

|        |   |     |
|--------|---|-----|
| 8.2.2  | <i>The Classical Displacement Formulation</i>   | 273 |
| 8.2.3  | <i>The Mixed Displacement–Pressure Formulation</i>  | 275 |
| 8.3    | Porous and Poroelastic Material Data and Coefficients   | 277 |
| 8.3.1  | <i>Porous Materials with a Rigid Frame</i>  | 277 |
| 8.3.2  | <i>Poroelastic Materials</i>  | 278 |
| 8.4    | Weak Forms of Poroelasticity, Elasticity, Piezoelectricity and Acoustics                                    | 279 |
| 8.4.1  | <i>Weak Form of the Mixed Formulation of Poroelasticity</i>   | 279 |
| 8.4.2  | <i>Weak Form for an Elastic Solid</i>   | 280 |
| 8.4.3  | <i>Weak Form of Piezoelectricity</i>  | 282 |
| 8.4.4  | <i>Weak Form for an Acoustic Medium</i>   | 285 |
| 8.5    | Boundary Conditions for Poroelastic Medium  | 286 |
| 8.5.1  | <i>The Boundary Integral</i>  | 286 |
| 8.5.2  | <i>Imposed Displacement Field</i>   | 286 |
| 8.5.3  | <i>Imposed Pressure Field</i>   | 287 |
| 8.6    | Interface Coupling Conditions for Poroelastic and Other Media   | 288 |
| 8.6.1  | <i>Poroelastic–Poroelastic Coupling</i>   | 288 |
| 8.6.2  | <i>Poroelastic–Elastic Coupling</i>   | 288 |
| 8.6.3  | <i>Poroelastic–Acoustic Coupling</i>  | 289 |
| 8.6.4  | <i>Acoustic–Elastic Coupling</i>  | 290 |
| 8.7    | Galerkin Finite Element Model of a Coupled System of Piezoelectric, Elastic, Poroelastic and Acoustic Media | 290 |
| 8.7.1  | <i>A Coupled Multiphysics System</i>  | 290 |
| 8.7.2  | <i>Weak Form of the Coupled System</i>  | 293 |
| 8.7.3  | <i>Galerkin Finite Element Approximation</i>  | 294 |
| 8.7.4  | <i>Submatrices and Couplings in the Algebraic System</i>  | 298 |
| 8.8    | Modeling of Poroelastic Layers with Mass Implants Improving Acoustic Absorption                             | 300 |
| 8.8.1  | <i>Motivation</i>   | 300 |
| 8.8.2  | <i>Two Approaches in Modeling Small Solid Implants</i>  | 300 |
| 8.8.3  | <i>Acoustic Absorption of the Poroelastic Layer</i>   | 301 |
| 8.8.4  | <i>Results of Analyses</i>  | 301 |
| 8.8.5  | <i>Concluding Remarks</i>   | 304 |
| 8.9    | Designs of Active Elastoporoelastic Panels  | 304 |
| 8.9.1  | <i>Introduction</i>   | 304 |
| 8.9.2  | <i>Active Sandwich Panel</i>  | 305 |
| 8.9.3  | <i>Active Single-Plate Panel</i>  | 306 |
| 8.10   | Modeling and Analysis of an Active Single-Plate Panel   | 308 |
| 8.10.1 | <i>Kinds and Purposes of Numerical Tests</i>  | 308 |
| 8.10.2 | <i>Plate Tests</i>  | 309 |
| 8.10.3 | <i>Multilayer Analysis</i>  | 311 |
| 8.10.4 | <i>Analysis of Passive Behavior of the Panel</i>  | 313 |
| 8.10.5 | <i>Test of Active Behavior of the Panel</i>   | 315 |
| 8.10.6 | <i>Concluding Remarks</i>   | 318 |
|        | References  | 319 |

**Acknowledgements** **323**

**Index** **327**