

SMART STRUCTURES THEORY

The twenty-first century might be called the “Multifunctional Materials Age.” The inspiration for multifunctional materials comes from nature and therefore these are often referred to as “bio-inspired materials.” Bio-inspired materials encompass smart materials and structures, multifunctional materials, and nano-structured materials. This is a dawn of revolutionary materials that may provide a “quantum jump” in performance and multi-capability. This book focuses on smart materials, structures, and systems, which are also referred to as intelligent, adaptive, active, sensory, and metamorphic. The purpose of these materials from the perspective of smart systems is their ability to minimize life-cycle cost and/or expand the performance envelope. The ultimate goal is to develop biologically inspired multifunctional materials with the capability to adapt their structural characteristics (e.g., stiffness, damping, and viscosity) as required, monitor their health condition, perform self-diagnosis and self-repair, morph their shape, and undergo significant controlled motion over a wide range of operating conditions.

Dr. Inderjit Chopra is an Alfred Gessow Professor in Aerospace Engineering and Director of the Alfred Gessow Rotorcraft Center at the University of Maryland. Dr. Chopra works on fundamental problems related to aeromechanics of helicopters including aeromechanical stability; active vibration control; modeling of composite blades; rotor-head health monitoring; aeroelastic optimization; smart structures; micro air vehicles; and comprehensive aeromechanics analyses of bearingless, tilt-rotor, servo-flap, coaxial, compound, teetering, and circulation control rotors. Dr. Chopra has authored more than 160 archival journal papers and 260 conference-proceedings papers. He has been an associate editor of the *Journal of the American Helicopter Society* (1987–91), the *AIAA Journal of Aircraft* (1987–present), and the *Journal of Intelligent Materials and Systems* (1997–present). He has been elected Fellow in the following societies: American Institute of Aeronautics and Astronautics, American Helicopter Society, American Society of Mechanical Engineers, Aeronautical Society of India, and National Institute of Aerospace.

Dr. Jayant Sirohi is an expert in high-power density–solid state actuators, multifunctional structures, multi-mission–capable micro/unmanned aerial vehicles, and rotorcraft design. He is a professor in the Aerospace Engineering and Engineering Mechanics Department at the University of Texas at Austin. Dr. Sirohi previously worked at Sikorsky Aircraft Corporation, where he was a Staff Engineer in the Advanced Concept group.

Cambridge University Press
978-0-521-86657-6 - Smart Structures Theory
Inderjit Chopra and Jayant Sirohi
Frontmatter
[More information](#)

Cambridge Aerospace Series

Editors: Wei Shyy and Vigor Yang

1. J. M. Rolfe and K. J. Staples (eds.): *Flight Simulation*
2. P. Berlin: *The Geostationary Applications Satellite*
3. M. J. T. Smith: *Aircraft Noise*
4. N. X. Vinh: *Flight Mechanics of High-Performance Aircraft*
5. W. A. Mair and D. L. Birdsall: *Aircraft Performance*
6. M. J. Abzug and E. E. Larrabee: *Airplane Stability and Control*
7. M. J. Sidi: *Spacecraft Dynamics and Control*
8. J. D. Anderson: *A History of Aerodynamics*
9. A. M. Cruise, J. A. Bowles, C. V. Goodall, and T. J. Patrick: *Principles of Space Instrument Design*
10. G. A. Khoury (ed.): *Airship Technology*, Second Edition
11. J. P. Fielding: *Introduction to Aircraft Design*
12. J. G. Leishman: *Principles of Helicopter Aerodynamics*, Second Edition
13. J. Katz and A. Plotkin: *Low-Speed Aerodynamics*, Second Edition
14. M. J. Abzug and E. E. Larrabee: *Airplane Stability and Control: A History of the Technologies that Made Aviation Possible*, Second Edition
15. D. H. Hodges and G. A. Pierce: *Introduction to Structural Dynamics and Aeroelasticity*, Second Edition
16. W. Fehse: *Automatic Rendezvous and Docking of Spacecraft*
17. R. D. Flack: *Fundamentals of Jet Propulsion with Applications*
18. E. A. Baskharone: *Principles of Turbomachinery in Air-Breathing Engines*
19. D. D. Knight: *Numerical Methods for High-Speed Flows*
20. C. A. Wagner, T. Hüttl, and P. Sagaut (eds.): *Large-Eddy Simulation for Acoustics*
21. D. D. Joseph, T. Funada, and J. Wang: *Potential Flows of Viscous and Viscoelastic Fluids*
22. W. Shyy, Y. Lian, H. Liu, J. Tang, and D. Viieru: *Aerodynamics of Low Reynolds Number Flyers*
23. J. H. Saleh: *Analyses for Durability and System Design Lifetime*
24. B. K. Donaldson: *Analysis of Aircraft Structures*, Second Edition
25. C. Segal: *The Scramjet Engine: Processes and Characteristics*
26. J. F. Doyle: *Guided Explorations of the Mechanics of Solids and Structures*
27. A. K. Kundu: *Aircraft Design*
28. M. I. Friswell, J. E. T. Penny, S. D. Garvey, and A. W. Lees: *Dynamics of Rotating Machines*
29. B. A. Conway (ed.): *Spacecraft Trajectory Optimization*
30. R. J. Adrian and J. Westerweel: *Particle Image Velocimetry*
31. G. A. Flandro, H. M. McMahon, and R. L. Roach: *Basic Aerodynamics*
32. H. Babinsky and J. K. Harvey: *Shock Wave–Boundary-Layer Interactions*
33. C. K. W. Tam: *Computational Aeroacoustics: A Wave Number Approach*
34. A. Filippone: *Advanced Aircraft Flight Performance*
35. I. Chopra and J. Sirohi: *Smart Structures Theory*
36. W. Johnson: *Rotorcraft Aeromechanics*
37. W. Shyy, H. Aono, C. K. Kang, and H. Liu: *An Introduction to Flapping Wing Aerodynamics*
38. T. C. Lieuwen and V. Yang: *Gas Turbine Engines*

Cambridge University Press
978-0-521-86657-6 - Smart Structures Theory
Inderjit Chopra and Jayant Sirohi
Frontmatter
[More information](#)

Cambridge University Press
978-0-521-86657-6 - Smart Structures Theory
Inderjit Chopra and Jayant Sirohi
Frontmatter
[More information](#)

Smart Structures Theory

Inderjit Chopra

University of Maryland

Jayant Sirohi

The University of Texas at Austin



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-0-521-86657-6 - Smart Structures Theory
Inderjit Chopra and Jayant Sirohi
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS

32 Avenue of the Americas, New York, NY 10013-2473, USA

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9780521866576

© Inderjit Chopra and Jayant Sirohi 2014

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2014

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication Data

Chopra, Inderjit.

Smart structures theory / Inderjit Chopra, Jayant Sirohi. – First edition.

pages cm. – (Cambridge aerospace series ; 35)

Includes bibliographical references and index.

ISBN 978-0-521-86657-6 (hardback)

1. Smart materials – Industrial applications. 2. Smart structures – Industrial applications. I. Sirohi, Jayant. II. Title.

TA418.9.S62C47 2013

620.1'12–dc23 2013018869

ISBN 978-0-521-86657-6 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party Internet Web sites referred to in this publication and does not guarantee that any content on such Web sites is, or will remain, accurate or appropriate.

Contents

<i>Preface</i>	<i>page xvii</i>
1 Historical Developments and Potential Applications: Smart Materials and Structures	1
1.1 Smart Structures	3
1.1.1 Smart Material Actuators and Sensors	4
1.1.2 Smart Actuators	7
1.1.3 Sensors	8
1.1.4 Actuator-Sensor Synthesis	8
1.1.5 Control Methodologies	9
1.2 Manufacturing Issues	10
1.3 Piezoelectricity	10
1.4 Shape Memory Alloys	14
1.5 Electrostrictives	19
1.6 Magnetostrictives	21
1.6.1 Terfenol-D	22
1.6.2 Galfenol	24
1.7 ER and MR Fluids	25
1.8 Capability of Currently Available Smart Materials	29
1.9 Smart Structures Programs	31
1.9.1 Space Systems	35
1.9.2 Fixed-Wing Aircraft	41
1.9.3 Jet Engines	51
1.9.4 Rotary-Wing Aircraft	53
1.9.5 Civil Structures	61
1.9.6 Machine Tools	68
1.9.7 Automotive Systems	71
1.9.8 Marine Systems	75
1.9.9 Medical Systems	77
1.9.10 Electronics Equipment	86
1.9.11 Rail	88
1.9.12 Robots	89
1.9.13 Energy Harvesting	90

2 Piezoelectric Actuators and Sensors	113
2.1 Fundamentals of Piezoelectricity	113
2.2 Piezoceramics	117
2.3 Soft and Hard Piezoelectric Ceramics	119
2.4 Basic Piezoceramic Characteristics	119
2.5 Electromechanical Constitutive Equations	122
2.5.1 Piezoceramic Actuator Equations	124
2.5.2 Piezoceramic Sensor Equations	130
2.5.3 Alternate Forms of the Constitutive Equations	134
2.5.4 Piezoelectric Coupling Coefficients	137
2.5.5 Actuator Performance and Load Line Analysis	140
2.6 Hysteresis and Nonlinearities in Piezoelectric Materials	145
2.7 Piezoceramic Actuators	146
2.7.1 Behavior under Static Excitation Fields	147
2.7.2 Behavior under Dynamic Excitation Fields	154
2.7.3 Depoling Behavior and Dielectric Breakdown	161
2.7.4 Power Consumption	163
2.8 Equivalent Circuits to Model Piezoceramic Actuators	170
2.8.1 Curie Temperature	172
2.8.2 Cement-Based Piezoelectric Composites	172
2.8.3 Shape Memory Ceramic Actuators	172
2.9 Piezoelectric Sensors	173
2.9.1 Basic Sensing Mechanism	174
2.9.2 Bimorph as a Sensor	175
2.9.3 Signal-Conditioning Electronics	176
2.9.4 Sensor Calibration	181
3 Shape Memory Alloys (SMAs)	194
3.1 Fundamentals of SMA Behavior	197
3.1.1 Phase Transformation	197
3.1.2 Lattice Structure and Deformation Mechanism	198
3.1.3 Low-Temperature Stress-Strain Curve	200
3.1.4 Origin of the One-Way SME	201
3.1.5 Stress-Induced Martensite and Pseudoelasticity	203
3.1.6 Two-Way SME	208
3.1.7 All-Round SME	212
3.1.8 R-Phase Transformation	213
3.1.9 Porous SMA	214
3.2 Constrained Behavior of SMA	214
3.2.1 Free Recovery	215
3.2.2 Constrained Recovery	215
3.2.3 Effective Load Lines of an SMA Wire Actuator	216
3.3 Constitutive Models	217
3.4 Quasi-Static Macroscopic Phenomenological Constitutive Models	217
3.4.1 Tanaka Model	218
3.4.2 Liang and Rogers Model	220
3.4.3 Brinson Model	221
3.4.4 Boyd and Lagoudas Model	227
3.4.5 Other SMA Models	228

Contents

ix

3.5	Testing of SMA Wires	229
3.5.1	Sample Preparation, Cycling, and Annealing	229
3.5.2	Transformation Temperatures under Zero Stress	231
3.5.3	Variation of Transformation Temperatures with Stress	233
3.5.4	Stress-Strain Behavior at Constant Temperature	236
3.5.5	Stress-Temperature Behavior at Constant Strain	238
3.5.6	Comparison of Resistive Heating and External Heating	241
3.6	Obtaining Critical Points and Model Parameters from Experimental Data	243
3.7	Comparison of Constitutive Models with Experiments	246
3.8	Constrained Recovery Behavior (Stress versus Temperature) at Constant Strain	249
3.8.1	Worked Example	251
3.8.2	Worked Example	253
3.9	Damping Capacity of SMA	256
3.10	Differences in Stress-Strain Behavior in Tension and Compression	258
3.11	Non-Quasi-Static Behavior	259
3.11.1	Stress-Relaxation	260
3.11.2	Effect of Strain Rate	261
3.11.3	Modeling Non-Quasi-Static Behavior	261
3.11.4	Rate Form of Quasi-Static SMA Constitutive Models	263
3.11.5	Thermomechanical Energy Equilibrium	264
3.11.6	Cyclic Loading	268
3.12	Power Requirements for SMA Activation	269
3.12.1	Power Input: Resistance Behavior of SMA Wires	269
3.12.2	Heat Absorbed by the SMA Wire	271
3.12.3	Heat Dissipation	272
3.13	Torsional Analysis of SMA Rods and Tubes	272
3.13.1	Validation with Test Data	276
3.13.2	Constrained Recovery Behavior	279
3.14	Composite Structures with Embedded SMA Wires	281
3.14.1	Variable Stiffness Composite Beams	282
3.14.2	SMA-in-Sleeve Concept	284
3.14.3	Beams with Embedded SMA Wires	286
3.14.4	Power Requirements for Activation of SMA in Structures	289
3.14.5	Fabrication of Variable Stiffness Composite Beams	292
3.14.6	Experimental Testing of Variable Stiffness Beams	294
3.15	Concluding Remarks	297
4	Beam Modeling with Induced-Strain Actuation	305
4.1	Material Elastic Constants	305
4.2	Basic Definitions: Stress, Strains, and Displacements	312
4.2.1	Beams	315
4.2.2	Transverse Deflection of Uniform Isotropic Beams	318
4.3	Simple Blocked-Force Beam Model (Pin Force Model)	320
4.3.1	Single Actuator Characteristics	320
4.3.2	Dual Actuators: Symmetric Actuation	321
4.3.3	Single Actuator: Asymmetric Actuation	327
4.3.4	Unequal Electric Voltage ($V_{\text{top}} \neq V_{\text{bottom}}$)	329

4.3.5	Dissimilar Actuators: Piezo Thickness ($t_{c_{top}} \neq t_{c_{bottom}}$)	330
4.3.6	Dissimilar Actuators: Piezo Constants ($d_{31_{top}} \neq d_{31_{bottom}}$)	332
4.3.7	Worked Example	333
4.4	Uniform-Strain Model	337
4.4.1	Dual Actuators: Symmetric Actuation	338
4.4.2	Single Actuator: Asymmetric Actuation	347
4.4.3	Unequal Electric Voltage ($V_{top} \neq V_{bottom}$)	354
4.4.4	Dissimilar Actuators: Piezo Thickness ($t_{c_{top}} \neq t_{c_{bottom}}$)	355
4.4.5	Dissimilar Actuators: Piezo Constants ($d_{31_{top}} \neq d_{31_{bottom}}$)	355
4.4.6	Worked Example	356
4.5	Euler-Bernoulli Beam Model	361
4.5.1	Dual Actuators: Symmetric Actuation	361
4.5.2	Single Actuator: Asymmetric Actuation	368
4.5.3	Unequal Electric Voltage ($V_{top} \neq V_{bottom}$)	370
4.5.4	Dissimilar Actuators: Piezo Thickness ($t_{c_{top}} \neq t_{c_{bottom}}$)	371
4.5.5	Dissimilar Actuators: Piezo Constants ($d_{31_{top}} \neq d_{31_{bottom}}$)	371
4.5.6	Worked Example	372
4.5.7	Bimorph Actuators	375
4.5.8	Induced Beam Response Using Euler-Bernoulli Modeling	377
4.5.9	Embedded Actuators	379
4.5.10	Worked Example	381
4.6	Testing of a Beam with Surface-Mounted Piezoactuators	383
4.6.1	Actuator Configuration	383
4.6.2	Beam Configuration and Wiring of Piezo	383
4.6.3	Procedure	384
4.6.4	Measurement of Tip Slope	384
4.6.5	Data Processing	385
4.7	Extension-Bending-Torsion Beam Model	385
4.8	Beam Equilibrium Equations	391
4.9	Energy Principles and Approximate Solutions	391
4.9.1	Energy Formulation: Uniform-Strain Model	392
4.9.2	Energy Formulation: Euler-Bernoulli Model	395
4.9.3	Galerkin Method	397
4.9.4	Worked Example	399
4.9.5	Worked Example	400
4.9.6	Rayleigh-Ritz Method	401
4.9.7	Worked Example	405
4.9.8	Worked Example	406
4.9.9	Energy Formulation: Dynamic Beam Governing Equation Derived from Hamilton's Principle	408
4.10	Finite Element Analysis with Induced-Strain Actuation	411
4.10.1	Behavior of a Single Element	412
4.10.2	Assembly of Global Mass and Stiffness Matrices	415
4.10.3	Beam Bending with Induced-Strain Actuation	416
4.10.4	Worked Example	418
4.11	First-Order Shear Deformation Theory (FSDT) for Beams with Induced-Strain Actuation	420
4.11.1	Formulation of the FSDT for a Beam	421
4.11.2	Shear Correction Factor	423

Contents

xi

4.11.3 Transverse Deflection of Uniform Isotropic Beams Including Shear Correction	424
4.11.4 Induced Beam Response Using Timoshenko Shear Model	426
4.11.5 Energy Formulation: FSDT	429
4.12 Layer-Wise Theories	431
4.13 Review of Beam Modeling	432
5 Plate Modeling with Induced-Strain Actuation	446
5.1 Classical Laminated Plate Theory (CLPT) Formulation without Actuation	446
5.1.1 Stress-Strain Relations for a Lamina at an Arbitrary Orientation	448
5.1.2 Macromechanical Behavior of a Laminate	450
5.1.3 Resultant Laminate Forces and Moments	452
5.1.4 Displacements-Based Governing Equations	456
5.1.5 Boundary Conditions	458
5.2 Plate Theory with Induced-Strain Actuation	460
5.2.1 Isotropic Plate: Symmetric Actuation (Extension)	463
5.2.2 Isotropic Plate: Antisymmetric Actuation (Bending)	465
5.2.3 Worked Example	467
5.2.4 Single-Layer Specially Orthotropic Plate (Extension)	469
5.2.5 Single-Layer Specially Orthotropic Plate (Bending)	471
5.2.6 Single-Layer Generally Orthotropic Plate (Extension)	472
5.2.7 Single-Layer Generally Orthotropic Plate (Bending)	473
5.2.8 Multilayered Symmetric Laminate Plate	474
5.2.9 Multilayered Antisymmetric Laminate Plate	477
5.2.10 Summary of Couplings in Plate Stiffness Matrices	480
5.2.11 Worked Example	481
5.3 Classical Laminated Plate Theory (CLPT) Equations in Terms of Displacements	486
5.4 Approximate Solutions Using Energy Principles	488
5.4.1 Galerkin Method	489
5.4.2 Rayleigh-Ritz Method	490
5.4.3 Symmetric Laminated Plate Response	492
5.4.4 Laminated Plate with Induced-Strain Actuation	494
5.4.5 Laminated Plate with Antisymmetric Layup: Extension-Torsion Coupling	499
5.4.6 Laminated Plate with Symmetric Layup: Bending-Torsion Coupling	502
5.4.7 Worked Example	506
5.4.8 Worked Example	512
5.4.9 Worked Example	517
5.5 Coupling Efficiency	521
5.5.1 Extension-Torsion Coupling Efficiency	521
5.5.2 Bending-Torsion Coupling Efficiency	523
5.5.3 Comparison of Extension-Torsion and Bending-Torsion Coupling	524
5.6 Classical Laminated Plate Theory (CLPT) with Induced-Strain Actuation for a Dynamic Case	527

5.7	Refined Plate Theories	531
5.8	Classical Laminated Plate Theory (CLPT) for Moderately Large Deflections	533
5.9	First-Order Shear Deformation Plate Theory (FSDT) with Induced-Strain Actuation	538
5.10	Shear Correction Factors	542
5.11	Effect of Laminate Kinematic Assumptions on Global Response	545
5.11.1	Effect of Two-Dimensional Mesh Density on the Computed Global Response	549
5.11.2	Pure-Extension Problem (Equal Voltages to Top and Bottom Actuators)	550
5.11.3	Pure-Bending Problem (Actuators Subjected to Equal but Opposite Voltages)	552
5.12	Effect of Transverse Kinematic Assumptions on Global Response	554
5.12.1	Case I: Pure-Extension Actuation	555
5.12.2	Case II: Pure-Bending Actuation	559
5.13	Effect of Finite Thickness Adhesive Bond Layer	562
5.13.1	Case I: Pure-Extension Actuation	563
5.13.2	Case II: Pure-Bending Actuation	565
5.14	Strain Energy Distribution	565
5.15	Review of Plate Modeling	573
6	Magnetostrictives and Electrostrictives	581
6.1	Magnetostriction	581
6.2	Review of Basic Concepts in Magnetism	584
6.2.1	Magnetic Field B and the Biot-Savart Law	585
6.2.2	Current Carrying Conductors	586
6.2.3	Magnetic Flux Φ and Magnetic Field Intensity H	590
6.2.4	Interaction of a Current Carrying Conductor and a Magnetic Field	591
6.2.5	Magnetization M , Permeability μ , and the B - H Curve	592
6.2.6	Demagnetization	595
6.2.7	Electrical Impedance	596
6.2.8	Systems of Units	596
6.2.9	Magnetic Circuits	597
6.3	Mechanism of Magnetostriction	599
6.3.1	Definition of Crystal Axes and Magnetic Anisotropy	599
6.3.2	Origin of the Magnetostrictive Effect	601
6.3.3	Effect of Magnetic Field Polarity	603
6.3.4	Effect of External Stresses	605
6.3.5	Effect of Temperature	607
6.3.6	Strain Hysteresis	608
6.4	Constitutive Relations	609
6.4.1	Linear Piezomagnetic Equations	611
6.4.2	Refined Magnetostrictive Models	613
6.4.3	Preisach Model	614
6.4.4	Energy Methods	615
6.5	Material Properties	616
6.5.1	Magnetomechanical Coupling	617

Contents

xiii

6.5.2	Worked Example	621
6.5.3	Delta-E Effect	622
6.5.4	Magnetostrictive Composites	624
6.6	Magnetostrictive Actuators	625
6.6.1	Generation of the Magnetic Field	627
6.6.2	Construction of a Typical Actuator	627
6.6.3	Measurement of Magnetic Field	628
6.6.4	DC Bias Field	629
6.6.5	Design of the Magnetic Field Generator for a Magnetostrictive Actuator	630
6.6.6	Worked Example: Design of a Magnetic Field Generator for a Magnetostrictive Actuator	634
6.6.7	Power Consumption and Eddy Current Losses	636
6.6.8	Magnetostrictive Particulate Actuators	639
6.7	Magnetostrictive Sensors	639
6.7.1	Worked Example	640
6.8	Iron-Gallium Alloys	641
6.9	Magnetic Shape Memory Alloys	643
6.9.1	Basic Mechanism	644
6.9.2	Effect of an External Magnetic Field	645
6.9.3	Effect of an External Stress	645
6.9.4	Behavior under a Combination of Magnetic Field and Compressive Stress	646
6.9.5	Dynamic Response	649
6.9.6	Comparison with SMAs	649
6.9.7	Experimental Behavior	651
6.9.8	MSMA Constitutive Modeling	653
6.9.9	Linear Actuator	655
6.9.10	Design of the Magnetic Field Generator (E-Frame)	656
6.9.11	Worked Example: Design of a Magnetic Field Generator (E-Frame)	659
6.10	Electrostrictives	662
6.10.1	Constitutive Relations	666
6.10.2	Behavior under Static Excitation Fields	670
6.10.3	Behavior under Dynamic Excitation Fields	673
6.10.4	Effect of Temperature	676
6.11	Polarization	677
6.12	Young's Modulus	678
6.13	Summary and Conclusions	678
7	Electrorheological and Magnetorheological Fluids	685
7.1	Fundamental Composition and Behavior of ER/MR Fluids	686
7.1.1	Composition of ER/MR Fluids	687
7.1.2	Viscosity	687
7.1.3	Origin of the Change in Viscosity	688
7.1.4	Yield Behavior	690
7.1.5	Temperature Dependence	692
7.1.6	Dynamic Behavior and Long-Term Effects	692
7.1.7	Comparison of ER and MR Fluids	693

7.2	Modeling of ER/MR Fluid Behavior and Device Performance	694
7.2.1	Equivalent Viscous Damping	695
7.2.2	Bingham Plastic Model	696
7.2.3	Herschel-Bulkley Model	697
7.2.4	Biviscous Model	697
7.2.5	Hysteretic Biviscous	698
7.2.6	Other Models	699
7.3	ER and MR Fluid Dampers	700
7.4	Modeling of ER/MR Fluid Dampers	704
7.4.1	Rectangular Flow Passage	705
7.4.2	Worked Example: Herschel-Bulkley Fluid Model	718
7.4.3	Worked Example: Bingham Biplastic Fluid Model	721
7.4.4	Annular Flow Passage	725
7.4.5	Squeeze Mode	734
7.5	Summary and Conclusions	735
8	Applications of Active Materials in Integrated Systems	739
8.1	Summary of Applications	739
8.1.1	Space Systems	741
8.1.2	Fixed-Wing Aircraft and Rotorcraft	741
8.1.3	Civil Structures	741
8.1.4	Machine Tools	742
8.1.5	Automotive	742
8.1.6	Marine Systems	742
8.1.7	Medical Systems	742
8.1.8	Electronic Equipment	742
8.1.9	Rail	743
8.1.10	Robots	743
8.1.11	Energy Harvesting	743
8.2	Solid-State Actuation and Stroke Amplification	743
8.2.1	Amplification by Means of Special Geometry or Arrangement of the Active Material	744
8.2.2	Amplification by External Leverage Mechanisms	755
8.2.3	Torsional Actuators	758
8.3	Double-Lever (L-L) Actuator	761
8.3.1	Positioning of the Hinges	761
8.3.2	Actuation Efficiency: Stiffness of the Actuator, Support, and Linkages	762
8.4	Energy Density	769
8.4.1	Worked Example	770
8.5	Stroke Amplification Using Frequency Rectification: The Piezoelectric Hybrid Hydraulic Actuator	772
8.5.1	Inchworm Motors	773
8.5.2	Ultrasonic Piezoelectric Motors	774
8.5.3	Hybrid Hydraulic Actuation Concept	775
8.5.4	Operating Principles	778
8.5.5	Active Material Load Line	779
8.5.6	Pumping Cycle	780
8.5.7	Energy Transfer	782

Contents

xv

8.5.8	Work Done Per Cycle	785
8.5.9	Maximum Output Work	786
8.5.10	Prototype Actuator	787
8.5.11	Experimental Testing	790
8.5.12	Modeling Approaches	796
8.5.13	Transmission-Line Approach	804
8.6	Smart Helicopter Rotor	810
8.6.1	Model-Scale Active Rotors	812
8.6.2	Full-Scale Active Rotors	817
8.6.3	Adaptive Controllers for Smart Rotors	819
8.7	SMA Actuated Tracking Tab for a Helicopter Rotor	823
8.7.1	Actuator Design Goals	824
8.7.2	Construction and Operating Principle	825
8.7.3	Blade Section Assembly	828
8.7.4	Modeling of the Device	828
8.7.5	Parametric Studies and Actuator Design	831
8.7.6	Results of Parametric Studies	832
8.7.7	Testing and Performance of the System	834
8.8	Tuning of Composite Beams	837
8.8.1	Fabrication of Composite Beams with SMA in Embedded Sleeves	837
8.8.2	Dynamic Testing of Composite Beams with SMA Wires	838
8.8.3	Free Vibration Analysis of Composite Beams with SMA Wires	838
8.8.4	Calculation of the Spring Coefficient of SMA Wire under Tension	840
8.8.5	Correlation with Test Data	841
8.9	Shunted Piezoelectrics	842
8.9.1	Principle of Operation	843
8.9.2	Types of Shunt Circuits	847
8.9.3	Worked Example	858
8.9.4	Worked Example	859
8.9.5	Worked Example	860
8.10	Energy Harvesting	863
8.10.1	Vibration-Based Energy Harvesters	863
8.10.2	Wind-Based Energy Harvesters	864
8.10.3	Modeling of Piezoelectric Energy Harvesters	864
8.10.4	Worked Example	870
8.10.5	Worked Example	872
8.10.6	Worked Example	876
8.11	Constrained Layer Damping	877
8.11.1	Active Constrained Layer Damping	880
8.12	Interior Noise Control	884
	<i>Index</i>	897

Cambridge University Press
978-0-521-86657-6 - Smart Structures Theory
Inderjit Chopra and Jayant Sirohi
Frontmatter
[More information](#)

Preface

In 1990, a pilot project was started at the Alfred Gessow Rotorcraft Center (University of Maryland) to build a smart rotor with embedded piezoelectric strips. Soon, it attracted the attention of Dr. Gary Anderson of the Army Research Office (ARO). He encouraged us to put together outlines for a major initiative in the smart structures area, which subsequently resulted in the award of a multi-year (1992–1997) University Research Initiative (URI). This provided us an opportunity to develop an effective team of interdisciplinary faculty from Aerospace, Mechanical, Electrical, and Material Engineering. As a result, there was an enormous growth of smart structures research activities on our campus. Following the success of this URI, we were awarded another multi-year (1996–2001) Multi University Research Initiative (MURI) in smart structures by ARO. For this major program, we collaborated with Penn State and Cornell University. This further nurtured the ongoing smart structures activities at Maryland. We deeply acknowledge the support and friendship of many faculty colleagues at Maryland: Appa Anjannappa, Bala Balachandran, James Baeder, Amr Baz, Roberto Celi, Ramesh Chandra, Abhijit Dasgupta, Allison Flatau, James Hubbard, P. S. Krishnaprasad, Gordon Leishman, V. T. Nagaraj, Darryll Pines, Don Robbins, Jim Sirkis, Fred Tasker, Norman Wereley, and Manfred Wuttig.

While the research frontier in smart structures was expanding at the Alfred Gessow Rotorcraft Center, we also initiated classroom teaching at the graduate level in the smart structures area. This textbook was developed from material covered in early versions of these class notes, and it aims to give a broad overview of smart materials and their applications in smart structures and integrated systems. The focus is on the fundamental physical phenomena observed in active materials and on the mathematical modeling of the coupled behavior of a smart structure with active material actuators and sensors. Simplistic descriptions of the physical mechanisms are given so that the reader can obtain an intuitive grasp of the fundamentals without having to delve deeply into rigorous solid mechanics concepts.

The research activities generated a large cadre of dissertations; many of these were pioneering foundational efforts in smart structures. We fondly acknowledge the contributions of our graduates: Jayasimha Atulsimha (VCU), Ron Barrett (Kansas), Oren Ben-Zeev (NAVAIR), Andy Bernhard (Sikorsky), Mike Bothwell (Bell), Peter Chen (IAI), Peter Copp (UMD), Ron Couch (APL), Anubhav Datta (NASA-Ames), Jeanette Epps (NASA-Astronaut), Farhan Gandhi (RPI),

Ranjan Ganguli (IISc), Gopal Kamath (Bombardier), Nikhil Koratkar (RPI), Taeoh Lee (Bell), Judah Milgram (NSWC-Carderock), Harsha Prahlad (SRI), Beatrice Roget (Wyoming), Jinwei Shen (NIA), Kiran Singh (Cambridge), Ed Smith (Penn State), Burtis Spencer (Air Force), Mike Spencer (Orbital Science), Curtis Walz (Boeing-Philadelphia), and Gang Wang (U. Huntsville).

During the 1990s, there was tremendous growth of smart structures activities in the United States and abroad. Many new conferences and workshops were initiated during this period, including: ARO Workshop in Smart Structures, SPIE Symposium in Smart Structures and Materials, AIAA Adaptive Structures Forum, ASME Adaptive Structures and Materials Systems (now called SMASIS), and ICAST (International Conference on Adaptive Structures and Technologies). These conferences and workshops not only helped to communicate our activities in smart structures but also provided avenues for meeting many great friends in this discipline. Over the years, we enjoyed the warmth of many friends in the United States and abroad, including V. K. Aatre (IISc), H. Abramovich (Technion), Diann Brei (Michigan), Flavio Campanile (EMPA), Greg Carman (UCLA), Carlos Cesnik (Michigan), Aditi Chattopadhyay (ASU), Eric Cross (Penn State), Marcello Dapino (OSU), Paolo Ermanni (ETH), Mary Frecker (Michigan), Mike Friswell (Swansea), Ephraim Garcia (Cornell), Paolo Gaudenzi (U. Rome), Victor Giurgiutiu (South Carolina), S. Gopalakrishnan (IISc), Z. Gurdal (Delft), Dan Inman (Michigan), Seung Jo Kim (KARI), A. V. Krishnamurthy (IISc), Dimitris Lagoudas (Texas A&M), C. K. Lee (National Taiwan), In Lee (KAIST), Jinsong Leng (Harbin), Don Leo (VPI), George Lesieutre (Penn State), Wei-Hsin Liao (Chinese University of Hong Kong), Chris Lynch (UCLA), John Main (VPI), Dave Martinez (Sandia), Yuji Matsuzaki (Nagoya), Peter Monner (DLR), M. C. Natori (Waseda), Fred Nitzsche (Carleton), Roger Ohayon (CNAM), Zoubeida Ounaies (Penn State), K. C. Park (Colorado), Jinhao Qui (Nanjing), Dimitris Saravanos (U. Patras), Janet Sater (IDA), Jonghwan Suhr (Delaware), J. Tani (Tohoku), Horn-Sen Tzou (Zhejiang), A. R. Upadhyaya (NAL), Ben Wada (JPL), Kon-Well Wang (Michigan), and Wenbin Yu (Utah).

We also collaborated with rotorcraft and other aerospace industries to transition this technology to full-scale systems. Under the DARPA Smart Rotor Program, Friedrich Straub and Hieu Ngo actively collaborated with the Alfred Gessow Rotorcraft Center and injected enthusiasm among our students. We again fondly acknowledge industrial friends in the United States and abroad, including Eric Anderson (CSA), Dan Clingman (Boeing), L. Porter Davis (Honeywell), Peter Jaenker (EADS), Shiv Joshi (NextGen), and Jay Kudva (NextGen). We would also like to thank the University of Maryland and the University of Texas at Austin, where we worked on material for this textbook.

Finally, we acknowledge our deep appreciation for the support and encouragement that we received from Dr. Gary Anderson, a true gentleman, who spearheaded the growth of smart structures activities in the United States. This book is dedicated to him.

Inderjit Chopra (University of Maryland)
 Jayant Sirohi (University of Texas at Austin)