# Contents

**Series editor's preface** *XV*
**Preface** *XVII*
**About the Volume Editors** *IX*
**List of Contributors** *XXI*

**Part I: Fundamentals** *1*

1 **Fundamental Theory of Resonant MEMS Devices** *3*
*Stephen M. Heinrich and Isabelle Dufour*
1.1 Introduction *3*
1.2 Nomenclature *4*
1.3 Single-Degree-of-Freedom (SDOF) Systems *5*
1.3.1 Free Vibration *6*
1.3.2 Harmonically Forced Vibration *8*
1.3.3 Contributions to Quality Factor from Multiple Sources *13*
1.4 Continuous Systems Modeling: Microcantilever Beam Example *14*
1.4.1 Modeling Assumptions *15*
1.4.2 Boundary Value Problem for a Vibrating Microcantilever *16*
1.4.3 Free-Vibration Response of Microcantilever *17*
1.4.4 Steady-State Response of a Harmonically Excited Microcantilever *19*
1.5 Formulas for Undamped Natural Frequencies *22*
1.5.1 Simple Deformations (Axial, Bending, Twisting) of 1D Structural Members: Cantilevers and Doubly Clamped Members ("Bridges") *23*
1.5.1.1 Axial Vibrations (Along x-Axis) *23*
1.5.1.2 Torsional Vibrations (Based on $h \ll b$) (Twist About x-Axis) *24*
1.5.1.3 Flexural (Bending) Vibrations *24*
1.5.2 Transverse Deflection of 2D Structures: Circular and Square Plates with Free and Clamped Supports *25*
1.5.3 Transverse Deflection of 1D Membrane Structures ("Strings") *25*

Bibliografische Informationen
http://d-nb.info/1058702874

digitalisiert durch DEUTSCHE NATIONAL BIBLIOTHEK

1.5.4 Transverse Deflection of 2D Membrane Structures: Circular and Square Membranes under Uniform Tension and Supported along Periphery *26*
1.5.5 In-Plane Deformation of Slender Circular Rings *26*
1.5.5.1 Extensional Modes *26*
1.5.5.2 In-Plane Bending Modes *26*
1.6 Summary *27*
Acknowledgment *27*
References *27*

**2 Frequency Response of Cantilever Beams Immersed in Viscous Fluids** *29*
*Cornelis Anthony van Eysden and John Elie Sader*
2.1 Introduction *29*
2.2 Low Order Modes *30*
2.2.1 Flexural Oscillation *30*
2.2.2 Torsional Oscillation *36*
2.2.3 In-Plane Flexural Oscillation *37*
2.2.4 Extensional Oscillation *37*
2.3 Arbitrary Mode Order *38*
2.3.1 Incompressible Flows *38*
2.3.2 Compressible Flows *46*
2.3.2.1 Scaling Analysis *47*
2.3.2.2 Numerical Results *48*
References *51*

**3 Damping in Resonant MEMS** *55*
*Shirin Ghaffari and Thomas William Kenny*
3.1 Introduction *55*
3.2 Air Damping *56*
3.3 Surface Damping *59*
3.4 Anchor Damping *61*
3.5 Electrical Damping *63*
3.6 Thermoelastic Dissipation (TED) *64*
3.7 Akhiezer Effect (AKE) *66*
References *69*

**4 Parametrically Excited Micro- and Nanosystems** *73*
*Jeffrey F. Rhoads, Congzhong Guo, and Gary K. Fedder*
4.1 Introduction *73*
4.2 Sources of Parametric Excitation in MEMS and NEMS *74*
4.2.1 Parametric Excitation via Electrostatic Transduction *75*
4.2.2 Other Sources of Parametric Excitation *77*
4.3 Modeling the Underlying Dynamics – Variants of the Mathieu Equation *77*

4.4 Perturbation Analysis *79*
4.5 Linear, Steady-State Behaviors *80*
4.6 Sources of Nonlinearity and Nonlinear Steady-State Behaviors *81*
4.7 Complex Dynamics in Parametrically Excited Micro/Nanosystems *84*
4.8 Combined Parametric and Direct Excitations *85*
4.9 Select Applications *85*
4.9.1 Resonant Mass Sensing *85*
4.9.2 Inertial Sensing *86*
4.9.3 Micromirror Actuation *87*
4.9.4 Bifurcation Control *88*
4.10 Some Parting Thoughts *89*
Acknowledgment *89*
References *89*

**5 Finite Element Modeling of Resonators** *97*
*Reza Abdolvand, Jonathan Gonzales, and Gavin Ho*
5.1 Introduction to Finite Element Analysis *97*
5.1.1 Mathematical Fundamentals *97*
5.1.1.1 Static Problems *98*
5.1.1.2 Dynamic Problems (Modal Analysis) *100*
5.1.2 Practical Implementation *101*
5.1.2.1 Set Up *102*
5.1.2.2 Processing *103*
5.1.2.3 Post-processing *103*
5.2 Application of FEA in MEMS Resonator Design *104*
5.2.1 Modal Analysis *104*
5.2.1.1 Mode Shape Analysis for Design Optimization *104*
5.2.1.2 Modeling Process-Induced Variation *108*
5.2.2 Loss Analysis *110*
5.2.2.1 Anchor Loss *110*
5.2.2.2 Thermoelastic Damping *112*
5.2.3 Frequency Response Analysis *113*
5.2.3.1 Spurious Mode Identification and Rejection *113*
5.2.3.2 Filter Design *115*
5.3 Summary *116*
References *116*

**Part II: Implementation** *119*

**6 Capacitive Resonators** *121*
*Gary K. Fedder*
6.1 Introduction *121*
6.2 Capacitive Transduction *122*
6.3 Electromechanical Actuation *123*

6.3.1 Electromechanical Force Derivation *123*
6.3.2 Voltage Dependent Force Components *124*
6.4 Capacitive Sensing and Motional Capacitor Topologies *127*
6.4.1 Parallel-Moving Plates *127*
6.4.2 Perpendicular Moving Plates *129*
6.4.3 Electrostatic Spring Softening and Snap-In *132*
6.4.4 Angular Moving Plates *134*
6.5 Electrical Isolation *135*
6.6 Capacitive Resonator Circuit Models *136*
6.7 Capacitive Interfaces *138*
6.7.1 Transimpedance Amplifier *138*
6.7.2 High-Impedance Voltage Detection *142*
6.7.3 Switched-Capacitor Detection *142*
6.8 Conclusion *143*
Acknowledgment *144*
References *144*

**7 Piezoelectric Resonant MEMS** *147*
*Gianluca Piazza*
7.1 Introduction to Piezoelectric Resonant MEMS *147*
7.2 Fundamentals of Piezoelectricity and Piezoelectric Resonators *149*
7.3 Thin Film Piezoelectric Materials for Resonant MEMS *152*
7.4 Equivalent Electrical Circuit of Piezoelectric Resonant MEMS *153*
7.4.1 One-Port Piezoelectric Resonators *156*
7.4.2 Two-Port Piezoelectric Resonators *157*
7.4.3 Resonator Figure of Merit *158*
7.5 Examples of Piezoelectric Resonant MEMS: Vibrations in Beams, Membranes, and Plates *158*
7.5.1 Flexural Vibrations *159*
7.5.2 Width-Extensional Vibrations *163*
7.5.3 Thickness-Extensional and Shear Vibrations *166*
7.6 Conclusions *168*
References *169*

**8 Electrothermal Excitation of Resonant MEMS** *173*
*Oliver Brand and Siavash Pourkamali*
8.1 Basic Principles *173*
8.1.1 Fundamental Equations for Electro-Thermo-Mechanical Transduction *173*
8.1.2 Time Constants and Frequency Dependencies *175*
8.2 Actuator Implementations *178*
8.2.1 Thin-Film/Surface Actuators *179*
8.2.2 Bulk Actuators *184*
8.3 Piezoresistive Sensing *185*
8.3.1 Fundamental Equations for Piezoresistive Sensing *185*

8.3.2 Piezoresistor Implementations *187*
8.3.3 Self-Sustained Thermal-Piezoresistive Oscillators *189*
8.4 Modeling and Optimization of Single-Port Thermal-Piezoresistive Resonators *193*
8.4.1 Thermo-Electro-Mechanical Modeling *193*
8.4.2 Resonator Equivalent Electrical Circuit and Optimization *195*
8.5 Examples of Thermally Actuated Resonant MEMS *197*
References *199*

**9 Nanoelectromechanical Systems (NEMS)** *203*
*Liviu Nicu, Vaida Auzelyte, Luis Guillermo Villanueva, Nuria Barniol, Francesc Perez-Murano, Warner J. Venstra, Herre S. J. van der Zant, Gabriel Abadal, Veronica Savu, and Jürgen Brugger*
9.1 Introduction *203*
9.1.1 Fundamental Studies *203*
9.1.2 Transduction at the Nanoscale *206*
9.1.3 Materials, Fabrication, and System Integration *208*
9.1.4 Electronics *211*
9.1.5 Nonlinear MEMS/NEMS Applications *212*
9.2 Carbon-Based NEMS *215*
9.3 Toward Functional Bio-NEMS *219*
9.3.1 NEMS-Based Energy Harvesting: an Emerging Field *220*
9.4 Summary and Outlook *222*
References *224*

**10 Organic Resonant MEMS Devices** *233*
*Sylvan Schmid*
10.1 Introduction *233*
10.2 Device Designs *235*
10.2.1 Conductive Polymer with Electrostatic Actuation *235*
10.2.2 Dielectric Polymer with Polarization Force Actuation *236*
10.2.3 Superparamagnetic Nanoparticle Composite with Magnetic Actuation *238*
10.2.4 Metallized Polymer with Lorentz Force Actuation *239*
10.3 Quality Factor of Polymeric Micromechanical Resonators *242*
10.3.1 Quality Factor in Viscous Environment *242*
10.3.2 Quality Factor of Relaxed Resonators in Vacuum *242*
10.3.3 Quality Factor of Unrelaxed Resonators in Vacuum *243*
10.4 Applications *247*
10.4.1 Humidity Sensor *247*
10.4.2 Vibrational Energy Harvesting *252*
10.4.3 Artificial Cochlea *253*
References *256*

**11 Devices with Embedded Channels** *261*
*Thomas P. Burg*
11.1 Introduction *261*
11.2 Theory *263*
11.2.1 Effects of Fluid Density and Flow *263*
11.2.2 Effects of Viscosity on the Quality Factor *267*
11.2.3 Effect of Surface Reactions *269*
11.2.4 Single Particle Measurements *271*
11.3 Device Technology *273*
11.3.1 Fabrication *273*
11.3.2 Packaging Considerations *275*
11.4 Applications *279*
11.4.1 Measurements of Fluid Density and Mass Flow *279*
11.4.2 Single Particle and Single Cell Measurements *279*
11.4.3 Surface-Based Measurements *280*
11.5 Conclusion *282*
References *283*

**12 Hermetic Packaging for Resonant MEMS** *287*
*Matthew William Messana, Andrew Bradley Graham, and Thomas William Kenny*
12.1 Introduction *287*
12.2 Overview of Packaging Types *289*
12.3 Die-Level Vacuum-Can Packaging *291*
12.4 Wafer Bonding for Device Packaging *293*
12.5 Thin Film Encapsulation-Based Packaging *296*
12.6 Getters *298*
12.7 The "Stanford epi-Seal Process" for Packaging of MEMS Resonators *299*
12.8 Conclusion *302*
References *302*

**13 Compensation, Tuning, and Trimming of MEMS Resonators** *305*
*Roozbeh Tabrizian and Farrokh Ayazi*
13.1 Introduction *306*
13.2 Compensation Techniques in MEMS Resonators *306*
13.2.1 Compensation for Thermal Effects *306*
13.2.1.1 Engineering the Geometry *307*
13.2.1.2 Doping *307*
13.2.1.3 Composite Resonators *309*
13.2.2 Compensation for Manufacturing Uncertainties *313*
13.2.3 Compensation and Control of Quality Factor *315*
13.2.4 Compensation for Polarization Voltage *317*
13.3 Tuning Methods in MEMS Resonators *317*
13.3.1 Device Level Tuning *317*

13.3.1.1 Electrostatic Tuning *318*
13.3.1.2 Thermal Tuning *318*
13.3.1.3 Piezoelectric Tuning *319*
13.3.2 System-Level Tuning *320*
13.4 Trimming Methods *321*
References *322*

**Part III: Application** *327*

**14 MEMS Inertial Sensors** *329*
*Diego Emilio Serrano and Farrokh Ayazi*
14.1 Introduction *329*
14.2 Accelerometers *329*
14.2.1 Principles of Operation *330*
14.2.2 Quasi-Static Accelerometers *331*
14.2.2.1 Squeeze-Film Damping *332*
14.2.2.2 Electromechanical Transduction in Accelerometers *333*
14.2.2.3 Mechanical Noise in Accelerometers *334*
14.2.3 Resonant Accelerometers *334*
14.2.3.1 Electrostatic Spring-Softening *335*
14.2.3.2 Acceleration Sensitivity in Resonant Accelerometers *336*
14.3 Gyroscopes *336*
14.3.1 Principles of Operation *337*
14.3.1.1 Vibratory Gyroscopes *337*
14.3.1.2 Mode-Split versus Mode-Matched Gyroscopes *339*
14.3.2 Bulk-Acoustic Wave (BAW) Gyroscopes *341*
14.3.2.1 Angular Gain *342*
14.3.2.2 Zero-Rate Output *343*
14.3.2.3 ZRO Cancelation *345*
14.3.2.4 Electromechanical Transduction in Gyroscopes *345*
14.3.2.5 Electrostatic Mode Matching and Mode Alignment *346*
14.3.3 Mechanical Noise in Mode-Matched Gyroscopes *347*
14.4 Multi-degree-of-Freedom Inertial Measurement Units *348*
14.4.1 System-in-Package IMUs *348*
14.4.2 Single-Die IMUs *349*
14.4.3 Future Trends in Sensor Integration *351*
References *352*

**15 Resonant MEMS Chemical Sensors** *355*
*Luke A. Beardslee, Oliver Brand, and Fabien Josse*
15.1 Introduction *355*
15.2 Modeling of Resonant Microcantilever Chemical Sensors *357*
15.2.1 Generalized Resonant Frequency *360*
15.3 Effects of Chemical Analyte Sorption into the Coating *361*

15.3.1 Resonant Frequency *361*
15.3.2 Quality Factor *363*
15.4 Figures of Merit *364*
15.5 Chemically Sensitive Layers *368*
15.6 Packaging *371*
15.7 Gas-Phase Chemical Sensors *374*
15.8 Liquid-Phase Chemical Sensors *377*
15.8.1 Cantilevers *379*
15.8.2 Microdisk Resonators *380*
15.8.3 Acoustic Wave Sensors *381*
15.8.4 Resonators with Encapsulated Channels *383*
References *383*

**16 Biosensors** *391*
*Blake N. Johnson and Raj Mutharasan*
16.1 Introduction *391*
16.2 Design Considerations: Length Scale, Geometry, and Materials *392*
16.2.1 Fabrication Materials *392*
16.2.2 Single-Layer Geometry *402*
16.2.3 Multi-Layer Geometry *403*
16.2.4 Length Scales *403*
16.3 Surface Functionalization: Preparation, Passivation, and Bio-recognition *404*
16.3.1 Antibody-Based Bio-recognition *405*
16.3.2 Nucleic Acid-Based Bio-recognition *405*
16.3.3 Alternative Bio-recognition Agents *407*
16.4 Biosensing Application Formats *408*
16.4.1 Dip-Dry-Measure Method *408*
16.4.2 Continuous Flow Method *408*
16.5 Application Case Studies *409*
16.5.1 Whole Cells: Pathogens and Parasites *409*
16.5.1.1 Foodborne Pathogen: *Escherichia coli* O157:H7 *409*
16.5.1.2 Foodborne Pathogen: *Listeria monocytogenes* *411*
16.5.1.3 Waterborne Parasite: *Cryptosporidium parvum* *413*
16.5.1.4 Waterborne Parasite: *Giardia lamblia* *413*
16.5.2 Proteins: Biomarkers and Toxins *414*
16.5.2.1 Prostate Cancer Biomarker: Prostate Specific Antigen *414*
16.5.2.2 Prostate Cancer Biomarker: Alpha-methylacyl-CoA Racemase (AMACR) *414*
16.5.2.3 Toxin in Source Water: Microcystin *415*
16.5.2.4 Toxin in Food Matrices: *Staphylococcal enterotoxin* B *415*
16.5.3 Virus *416*
16.5.4 Nucleic Acids: Biomarkers and Genes Associated with Toxin Production *416*

16.5.4.1 RNA-Based Biomarkers: MicroRNA *416*
16.5.4.2 Gene Signature of a Virus *417*
16.5.4.3 Toxin-Associated Genes for Pathogen Detection without DNA Amplification *417*
16.6 Conclusions and Future Trends *418*
Acknowledgment *419*
References *419*

**17 Fluid Property Sensors** *427*
*Erwin K. Reichel, Martin Heinisch, and Bernhard Jakoby*
17.1 Introduction *427*
17.2 Definition of Fluid Properties *429*
17.2.1 Rheological Properties *429*
17.2.2 Time-Harmonic Deformation *431*
17.2.3 Classical Methods for Measuring Fluid Properties *431*
17.2.4 Miniaturized Rheometers *432*
17.3 Resonator Sensors *433*
17.3.1 Excitation and Readout *433*
17.3.2 Eigenmode Decomposition *433*
17.3.3 Electrical Equivalent Circuit *434*
17.3.4 Damping *435*
17.3.5 Fluid-Structure Interaction *436*
17.4 Examples of Resonant Sensors for Fluid Properties *438*
17.4.1 Microacoustic Devices *440*
17.4.2 MEMS Devices *441*
17.4.2.1 Cantilever Devices *441*
17.4.2.2 U-Shaped Cantilevers *445*
17.4.2.3 Tuning Forks *445*
17.4.2.4 Doubly-Clamped Beam Devices *445*
17.4.2.5 In-Plane Resonators *445*
17.4.2.6 Other Principles *445*
17.4.3 Comparison *446*
17.5 Conclusions *446*
References *446*

**18 Energy Harvesting Devices** *451*
*Stephen P. Beeby*
18.1 Introduction *451*
18.2 Generic Harvester Structures *452*
18.2.1 Inertial Energy Harvesters *453*
18.2.2 Direct Force Energy Harvesters *456*
18.2.3 Broadband Energy Harvesters *457*
18.2.4 Frequency Conversion *460*
18.3 MEMS Energy Harvester Transduction Mechanisms *461*
18.3.1 Piezoelectric Transduction *462*

18.3.2 Electromagnetic Transduction *464*
18.3.3 Electrostatic Transduction *465*
18.3.4 Other Transducer Materials *467*
18.4 Review and Comparison of MEMS Energy Harvesting Devices *468*
18.5 Conclusions *471*
References *472*

**Index** *475*