

Contents

1	MEMS, Their Features, and Modeling Challenges	1
1.1	What Are MEMS and Why They Are Attractive?	1
1.2	Why We Need Modeling and Simulation Tools?	4
1.3	Challenges of MEMS Modeling and Simulations	4
1.4	Coupled-Field MEMS Phenomena	7
1.4.1	Squeeze-Film Damping	7
1.4.2	Thermoelastic Damping	8
1.4.3	Pull-in Instability	8
1.4.4	Stiction Due to Capillary Forces	9
1.5	The State-of-the-Art of MEMS Modeling and Simulations	10
	Problems	11
	References	11
2	Vibrations of Lumped-Parameter Systems	13
2.1	Introduction	13
2.2	Free Vibration of Single-Degree-of-Freedom Systems	14
2.2.1	Undamped Vibration	14
2.2.2	Damped Vibration	18
2.3	Forced Harmonic Excitation of Single-Degree-of-Freedom Systems	22
2.4	Vibrating MEMS Gyroscopes	28
2.5	Base Excitations of SDOF Systems and Accelerometers Principles	32
2.6	Response of SDOF Systems to Arbitrary Excitation	36
2.7	Vibrations of Two-Degree-of-Freedom Systems	40
2.7.1	Undamped Free Vibration and Eigenvalue Problem	40
2.7.2	Modal Analysis	43
2.7.3	Resonances in 2-DOF Systems	47
2.8	Numerical Integration	48

2.9	MEMS Band-Pass Filters	52
	Problems	54
	References	56
3	Sensing and Actuation in MEMS	57
3.1	Electrothermal Actuation	57
3.1.1	U-Shaped Actuator	58
3.1.2	V-Beam Actuator	59
3.1.3	Bimorph Actuator	60
3.2	Piezoelectric Actuation and Detection	61
3.3	Electromagnetic and Magnetic Actuation	65
3.4	Piezoresistive Detection	68
3.5	Electrostatic Actuation and Detection	70
3.5.1	Simple Parallel-Plate Capacitors	72
3.5.2	Torsional Actuators and Micromirrors	78
3.5.3	Comb-Drive Devices	82
3.6	Resonant Sensors	87
	Problems	91
	References	92
4	Elements of Lumped-Parameter Modeling in MEMS	97
4.1	Stiffness of Microstructures	97
4.1.1	Experimental Methods	98
4.1.2	Computational Methods	101
4.1.3	Analytical Methods	101
4.2	Spring–Mass Models	107
4.3	Damping in MEMS	111
4.3.1	Mechanisms of Energy Losses	112
4.3.2	Air Damping Fundamentals	114
4.3.3	Damping Dependence on Pressure: Newell’s Classification	116
4.3.4	Drag Force	117
4.3.5	Squeeze-Film Damping	118
4.3.6	Slide-Film Damping	139
4.3.7	Intrinsic Damping	142
4.3.8	Extracting Damping Coefficients Experimentally	143
	Problems	145
	References	150
5	Introduction to Nonlinear Dynamics	155
5.1	Introduction	155
5.2	Nondimensionalization	157
5.3	Fixed Points and Linearization	161
5.4	Bifurcations of Fixed Points	168
5.4.1	Saddle-Node Bifurcation	169
5.4.2	Transcritical Bifurcation	177

5.4.3	Pitchfork Bifurcation	178
5.4.4	Hopf Bifurcation	182
5.5	Phase Portraits	184
5.5.1	Phase Diagram of a Parallel-Plate Capacitor and the Dynamic Pull-in Concept	190
5.5.2	Phase Diagram of a Double-Sided Capacitor	194
5.6	Step-Input Actuation of Capacitive RF Switches	197
5.7	Dynamics of Torsional Actuators and Micromirrors	201
5.7.1	Single-Degree-of-Freedom Model	202
5.7.2	Two-Degree-of-Freedom Model	206
5.8	Nonlinear Oscillations	211
5.8.1	The Effect of a Constant Force	212
5.8.2	Free Vibration in the Presence of Nonlinearities	216
5.8.3	Forced Harmonic Vibration	217
5.8.4	Parametric Excitation	230
5.8.5	Self-Excited Oscillators	237
5.9	Modal Interaction, Chaos, and Fractal Behavior	239
	Problems	241
	References	245
6	Microbeams	251
6.1	The Linear Equation of Motion	251
6.1.1	Boundary Conditions	254
6.1.2	Beams Made of Different Material Layers	259
6.2	The Static Response	260
6.3	Residual Stresses and Nonideal Supports of Cantilever Microbeams	262
6.4	Natural Frequencies and Modeshapes	267
6.4.1	Nondimensionalization	272
6.4.2	Flexible (Nonideal) Supports	274
6.4.3	Cantilever Beam with a Lumped Mass at the Tip	277
6.5	The Effect of Axial Load on the Natural Frequency and the Buckling Limit	280
6.6	The Orthogonality of Modeshapes	284
6.7	Forced Vibrations and Modal Analysis	286
6.7.1	Undamped Response with no Axial Load	286
6.7.2	Adding Axial Force	290
6.7.3	Adding Damping	291
6.8	A Nonlinear Model of Beams with Midplane Stretching	292
6.9	Other Nonlinear Models of Beams	296
6.10	The Galerkin Discretization and Reduced-Order Modeling	297
6.10.1	The Galerkin Method	297
6.10.2	Beams with Midplane Stretching	299
6.11	Reduced-Order Model of Beams Under Electrostatic Force	302

6.12	The Static Behavior of Beams Under Electrostatic Force	306
6.12.1	Cantilever Microbeams	306
6.12.2	Clamped–Clamped Microbeams	308
6.12.3	Microbeams with Partial Electrodes and Initial Curvature	312
6.13	The Natural Frequencies Under Electrostatic Force	314
6.14	Pull-in Time of RF Switches	319
6.15	Resonators Under AC + DC Excitation	321
6.16	Atomic Force Microscopes	323
6.16.1	Introduction	323
6.16.2	Interaction Forces	325
6.16.3	AFM Models	327
6.16.4	AFM Under Lennard–Jones Force	330
6.17	Beams Under Capillary Forces	338
6.18	Coupled-Field Damping of Beams	343
6.18.1	Squeeze-Film Damping	343
6.18.2	Thermoelastic Damping	344
	Problems	348
	References	352
7	Nonlinear Dynamics of an Electrically Actuated Resonator	359
7.1	The Device and Experimental Setup	359
7.2	Initial Characterization and Parameters Extraction	360
7.3	Experimental Data for Large DC and AC Excitations	363
7.3.1	Primary Resonance	363
7.3.2	Subharmonic Resonance	365
7.4	Simulations Using Long-Time Integration	368
7.5	Simulations Using the Shooting Technique	369
7.5.1	The Shooting Method	369
7.5.2	Results	372
7.6	Basin of Attraction Analysis	376
7.7	Attractors Tracking and the Integrity Factor	379
7.8	Remarks on Resonant Dynamic Pull-in	384
7.9	Mass Detection Application	386
7.10	Controlling Resonant Dynamic Pull-in	391
7.10.1	Introduction	391
7.10.2	Simulation and Experimental Results	392
7.10.3	Integrity Analysis	395
	Problems	397
	References	398
8	Mechanical Shock in MEMS	401
8.1	Introduction	401
8.2	Mechanical Shock	403
8.3	Modeling Shock in Lumped-Parameter Models	405

8.4	The Shock-Response Spectrum	407
8.5	Modeling Shock on Microbeams	409
8.6	Computationally Efficient Approach for Microstructures	411
8.7	High- g Shock Response	413
8.8	The Combined Effect of Shock and Electrostatic Forces	414
8.8.1	Single-Degree-of-Freedom Model	414
8.8.2	Beam Model	418
8.8.3	Switch Application	421
8.8.4	Experiments	421
8.9	Resonators Under Shock	426
8.9.1	Simulations	426
8.9.2	Experimental Results and Comparison with Simulations	429
8.10	The Effect of the PCB Motion	435
	Problems	439
	References	440
Appendix A		443
Index		451