

SPIE.

Power Harvesting via Smart Materials



Ashok K. Batra

Almuatasim Alomari

pbt

๕๖๘๘๕๐-

๑ 16489594
012496546
1 22095994

Power Harvesting via Smart Materials

Ashok K. Batra
Almuatasim Alomari



SPIE PRESS
Bellingham, Washington USA

Contents

<i>Foreword I</i>	<i>xi</i>
<i>Foreword II</i>	<i>xiii</i>
<i>Preface</i>	<i>xv</i>
<i>Acknowledgments</i>	<i>xvii</i>
<i>Glossary of Symbols and Abbreviations</i>	<i>xix</i>
1 Ambient Energy Sources: Mechanical, Light, and Thermal	1
1.1 Toward a New World Based on Green Energy	1
1.2 Vibration-to-Electricity Conversion	3
1.2.1 Electrostatic energy harvesting	4
1.2.2 Electromagnetic energy harvesting	4
1.2.3 Piezoelectric energy harvesting	5
1.2.4 Magnetostrictive energy harvesting	6
1.2.5 Photovoltaic energy harvesting	6
1.2.6 Radio-frequency energy harvesting	7
1.3 Thermal-to-Electricity Conversion	8
1.3.1 Seebeck-effect thermoelectric generator	9
1.3.2 Peltier-effect thermoelectric cooling	10
1.3.3 Thermoelectric materials	10
1.4 Commercial Energy-Harvesting Devices	11
References	14
2 Fundamentals of Ferroelectric Materials	17
2.1 Classification of Dielectric Materials	17
2.2 Important Dielectric Parameters	21
2.2.1 Electric dipole moment	21
2.2.2 Polar and nonpolar dielectric materials	21
2.2.3 Electric polarization	22
2.2.4 Electric displacement, dielectric constant, and electric susceptibility	22
2.2.5 Spontaneous polarization	23
2.3 Electrostrictive Effect	23
2.4 Piezoelectric Phenomena	24

2.5	Pyroelectric Phenomenon	26
2.5.1	Pyroelectric current generation	28
2.6	Ferroelectric Phenomena	29
2.6.1	Ferroelectric domains	31
2.6.2	Ferroelectric hysteresis	31
2.6.3	Poling	32
2.6.4	Paraelectric effect	33
2.7	Conclusion	33
	References	34
3	Piezoelectric Energy Harvesting	35
3.1	Historical Introduction of Piezoelectricity	36
3.2	Mechanism for Piezoelectricity	41
3.3	Theory of Dielectricity	43
3.3.1	Static fields	43
3.3.2	Time-dependent fields	44
3.4	Fundamentals of Electric Energy Harvesting	45
3.5	Piezoelectric Coefficients	46
3.5.1	Piezoelectric charge coefficient (d_{ij})	46
3.5.2	Piezoelectric voltage coefficient (g_{ij})	46
3.5.3	Dielectric constant (ϵ_{ij})	46
3.5.4	Coupling coefficient (k_{ij})	46
3.6	Electromechanical Properties of Piezoelectric Materials	47
3.6.1	Piezoelectric constitutive equations	47
3.6.2	Piezoelectric polymers	48
3.6.3	Piezoelectric ceramic: properties of PZT	52
3.6.4	Properties of single-crystal PMN-PT	52
3.7	Piezoelectric Effect for Energy Harvesting	53
3.7.1	General theory of mechanical energy conversion	53
3.7.2	Piezoelectric generators	54
3.8	Operating Principle of a Piezoelectric Generator System	54
3.8.1	Mechanical energy source	55
3.8.2	Mechanical transformers	55
3.8.3	Piezoelectric materials	55
3.8.4	Power-transfer electronics	56
3.8.5	Intelligent energy and storage management	56
3.9	Cantilevered Energy Harvesters and Types of Cantilever Beam	57
3.9.1	Unimorph cantilever	57
3.9.2	Bimorph cantilever	58
3.9.3	Multimorph cantilever	58
3.10	Modeling Cantilever Beams	59
3.11	Piezoelectric Energy Harvesting: A Recent Survey	60
3.12	Conclusion	63
	References	63

4	Parametric Identification and Measurement Techniques for Piezoelectric Energy Harvesters	79
4.1	General Electrical Parameters	79
4.2	Determining Piezoelectric Sensor Coefficients	79
4.2.1	Mechanical model and equivalent electrical circuit	79
4.2.2	Linear piezoelectric model	82
4.3	Electromechanical Coupling Coefficients	83
4.4	Elastic Compliance	84
4.5	Piezoelectric Charge Constants	85
4.6	Piezoelectric Voltage Constants	85
4.7	Mechanical Quality Factor	85
4.8	Methods for Measuring the Physical Properties of Ferroelectric Materials	85
4.8.1	Determining the dielectric properties of ferroelectrics	86
4.8.1.1	Dielectric constants and dielectric spectrum measurements at a low frequency	86
4.8.1.2	Polarization (hysteresis loop) measurements	87
4.8.2	Determination of piezoelectric coefficients	88
4.8.2.1	Berlincourt method for measuring \bar{d}_{33} and \bar{d}_{31}	88
4.8.2.2	Impedance analysis for measuring \bar{s}_{33}^E , \bar{s}_{33}^D , and \bar{k}_{33}	90
4.8.3	Pyroelectric coefficient measurements	91
4.8.3.1	Pyroelectric current method	91
4.8.3.2	Pyroelectric charge-integration method	92
4.9	Parametric Identification and Determination for Piezoelectric Energy Harvesters	92
4.9.1	Natural frequency identification	94
4.9.2	Damping factor identification	94
4.9.3	Quality-factor identification	95
4.9.4	Efficiency of energy conversion	95
4.10	Conclusion	96
	References	96
5	Theoretical Background of Mechanical Energy Conversion	97
5.1	Euler–Bernoulli Beam	98
5.2	Piezoelectric Cantilevered Beam Using the Euler–Bernoulli Theory	102
5.2.1	Clamped–free piezoelectric cantilever beam	102
5.2.2	Clamped–clamped piezoelectric cantilever beam	108
5.2.3	Clamped–free piezoelectric cantilever beam with tip mass	117
5.3	Lumped Parameter Model	119
5.3.1	Single degree of freedom	120
5.3.2	Two degrees of freedom	122
5.3.3	Three degrees of freedom	123

5.3.4	Lumped parameter model for MEMS applications	131
5.3.5	SDOF for a PMN-PT single crystal in d_{31}	133
5.3.6	Further piezoelectric applications of the Euler–Bernoulli beam theory	135
5.3.6.1	Nonpiezoelectric layer longer than the piezoelectric layer	135
5.3.6.2	Piezoelectric layer and nonpiezoelectric layer of equal length	136
5.3.6.3	Nonpiezoelectric layer shorter than the piezoelectric layer	136
5.3.7	Modeling the PZT sensor using the pin-force method, enhanced pin-force method, and Euler–Bernoulli theory	137
5.4	Further Applications of the 2DOF Model	138
5.5	Tapered Unimorph Beams	142
5.6	Trapezoidal Cantilever Beam	143
5.7	Multiple Piezoelectric Elements	144
5.7.1	Mathematical evaluation of a multiple-cantilever structure	144
5.7.2	Four cantilever-type legs and piezoelectric ceramics	148
5.8	Piezoelectric Energy Harvester with a Dynamic Magnifier	151
	References	160
6	Techniques for Enhancing Piezoelectric Energy-Harvesting Efficiency	165
6.1	Techniques to Tune the Resonant Frequency	165
6.2	Mechanical Tuning Techniques	166
6.2.1	Changing dimensions	166
6.2.2	Shifting the center of gravity of the proof mass	167
6.2.3	Varying the stiffness of the spring	169
6.2.4	Applying strain to the structure	169
6.3	Electrical Tuning Techniques	171
6.4	Bandwidth Widening Strategies	173
6.5	Conclusion	174
	References	175
7	Piezoelectric Power-Harvesting Devices	177
7.1	Flexible Piezoelectric Energy Harvesting from Jaw Movements	177
7.2	Piezoelectric Shoe-Mounted Harvesters	178
7.3	Piezo-Wind Generators	179
7.4	Rotary Knee-Joint Harvester	179
7.5	Piezoelectric Prosthetic-Leg Energy Harvesters	180
7.6	Piezoelectric Pacemaker	180
7.7	Piezoelectric Railways	180
7.8	Piezoelectric Roads and Highways	180
7.9	Flexible Wearable Harvester	181
7.10	Rotating Energy Harvesters	181

7.11	Water-Flow-Based Energy Harvester	182
7.12	Summary and Outlook	182
	References	182
8	Ferroelectric Energy Harvesting	185
8.1	Energy Transfer in Pyroelectrics	186
8.1.1	Ferroelectric effect	187
8.1.2	Paraelectric effect	188
8.1.3	Phase transitions	188
8.1.4	Pyroelectric performance	189
8.2	Thermodynamic Cycles for Pyroelectric Energy Conversion	189
8.2.1	Heat and work fundamentals	190
8.2.2	Pyroelectric energy-harvesting efficiency	194
8.2.3	Carnot cycle	194
8.2.4	Ericsson cycle	196
8.2.5	Lenoir cycle	197
8.2.6	Pyroelectric energy conversion based on the Clingman cycle	198
8.2.7	Pyroelectric energy conversion based on the Olsen cycle	199
8.3	Recent Progress in Pyroelectric Energy Conversion and Harvesting	201
8.3.1	Pyroelectric energy harvesting based on the direct pyroelectric effect	201
8.3.2	Pyroelectric energy-harvesting figures of merit	202
8.3.3	Pyroelectric energy conversion based on thermodynamic cycles	220
8.4	Conclusion	225
	References	225
9	Processing Important Piezoelectric Materials	233
9.1	Single Crystals	234
9.1.1	Growth of crystals from solution	234
9.1.2	Crystal growth from melt	236
9.1.3	High-temperature-flux method	237
9.1.4	Vertical-gradient-freeze method with no flux	238
9.2	Preparation of Ceramics	241
9.3	Thin-Film-Deposition Techniques	241
9.3.1	Non-solution-deposition techniques	242
9.3.1.1	Sputtering	242
9.3.1.2	Laser ablation	242
9.3.1.3	Chemical vapor deposition	243
9.3.2	Solution-deposition techniques	244
9.3.2.1	Sol-gel	244
9.3.2.2	Metal-organic deposition	246
9.3.2.2.1	Precursor synthesis	246
9.3.2.2.2	Solvent	247

9.3.2.2.3 Spin coating and pyrolysis	248
9.3.2.2.4 PZT films from MOD	249
9.4 Thick-Film Fabrication	250
9.4.1 Thick-film-transfer technology (screen printing)	250
9.5 Fabrication of Polymer–Ceramic Composites	251
References	253
10 Future Directions and Outlook	257
10.1 The Future of Power Harvesting: Drivers and Challenges	257
References	259
Appendix: MATLAB Codes	261
A.1 Euler–Bernoulli Clamped–Free Beam Modeling	261
A.2 Euler–Bernoulli Clamped–Free Unimorph Beam Modeling for Performance Parameters	263
A.3 Clamped–Clamped Beam Modeling for Performance Parameters	265
A.4 Clamped–Clamped Piezoelectric Cantilever Beam Modeling	267
A.5 Modeling the Performance Parameters of a PMN-PT Single Crystal with a Tip Mass Cantilever Beam	269
A.6 Modeling 2DOF Piezoelectric Vibrational Energy-Harvesting Parameters	272
A.7 Modeling 3DOF Piezoelectric Vibration Energy Harvesting	273
A.8 Modeling a 2DOF Cantilevered Beam System with Two Piezo Elements	274
A.9 Modeling a Thick Film Bonded to the Clamped End of an Aluminum Cantilever Beam	275
<i>Index</i>	279