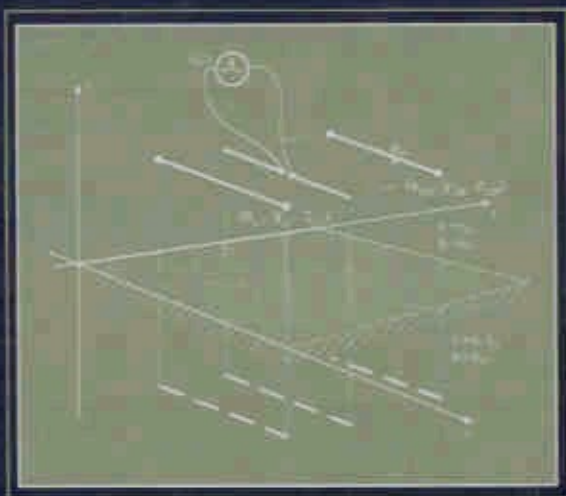


Advanced Modeling in
**Computational
Electromagnetic
Compatibility**



DRAGAN POLJAK

CONTENTS

PREFACE	xv
PART I: FUNDAMENTAL CONCEPTS IN COMPUTATIONAL ELECTROMAGNETIC COMPATIBILITY	1
1. Introduction to Computational Electromagnetics and Electromagnetic Compatibility	3
1.1 Historical Note on Modeling in Electromagnetics	3
1.2 Electromagnetic Compatibility and Electromagnetic Interference	5
1.2.1 EMC Computational Models and Solution Methods	5
1.2.2 Classification of EMC Models	7
1.2.3 Summary Remarks on EMC Modeling	8
1.3 References	8
2. Fundamentals of Electromagnetic Theory	10
2.1 Differential Form of Maxwell Equations	10
2.2 Integral Form of Maxwell Equations	11
2.3 Maxwell Equations for Moving Media	14
2.4 The Continuity Equation	17
2.5 Ohm's Law	19
2.6 Conservation Law in the Electromagnetic Field	21
2.7 The Electromagnetic Wave Equations	24
2.8 Boundary Relationships for Discontinuities in Material Properties	26
2.9 The Electromagnetic Potentials	32
2.10 Boundary Relationships for Potential Functions	33
2.11 Potential Wave Equations	35
2.11.1 Coulomb Gauge	36

2.11.2	Diffusion Gauge	37
2.11.3	Lorentz Gauge	38
2.12	Retarded Potentials	40
2.13	General Boundary Conditions and Uniqueness Theorem	41
2.14	Electric and Magnetic Walls	41
2.15	The Lagrangian Form of Electromagnetic Field Laws	42
2.15.1	Lagrangian Formulation and Hamilton Variational Principle	43
2.15.2	Lagrangian Formulation and Hamilton Variational Principle in Electromagnetics	45
2.16	Complex Phasor Notation of Time-Harmonic Electromagnetic Fields	51
2.16.1	Poynting Theorem for Complex Phasors	52
2.16.2	Complex Phasor Form of Electromagnetic Wave Equations	53
2.16.3	The Retarded Potentials for the Time-Harmonic Fields	54
2.17	Transmission Line Theory	54
2.17.1	Field Coupling Using Transmission Line Models	55
2.17.2	Derivation of Telegrapher's Equation for the Two-Wire Transmission Line	56
2.18	Plane Wave Propagation	66
2.19	Radiation	68
2.19.1	Radiation Mechanism	68
2.19.2	Hertzian Dipole	69
2.19.3	Fundamental Antenna Parameters	71
2.19.4	Linear Antennas	75
2.20	References	79
3	Introduction to Numerical Methods in Electromagnetics	80
3.1	Analytical Versus Numerical Methods	82
3.1.1	Frequency and Time Domain Modeling	82
3.2	Overview of Numerical Methods: Domain, Boundary, and Source Simulation	84
3.2.1	Modeling of Problems via the Domain Methods: FDM and FEM	84
3.2.2	Modeling of Problems via the BEM: Direct and Indirect Approach	85

3.3	The Finite Difference Method	85
3.3.1	One-Dimensional FDM	86
3.3.2	Two-Dimensional FDM	88
3.4	The Finite Element Method	91
3.4.1	Basic Concepts of FEM	91
3.4.2	One-Dimensional FEM	92
3.4.3	Two-Dimensional FEM	98
3.5	The Boundary Element Method	109
3.5.1	Integral Equation Formulation	109
3.5.2	Boundary Element Discretization	114
3.5.3	Computational Example for 2D Static Problem	121
3.6	References	122
4	Static Field Analysis	123
4.1	Electrostatic Fields	123
4.2	Magnetostatic Fields	124
4.3	Modeling of Static Field Problems	126
4.3.1	Integral Equations in Electrostatics Using Sources	126
4.3.2	Computational Example: Modeling of a Lightning Rod	129
4.4	References	135
5	Quasistatic Field Analysis	136
5.1	Introduction	136
5.2	Formulation of the Quasistatic Problem	137
5.3	Integral Equation Representation of the Helmholtz Equation	140
5.4	Computational Example	143
5.4.1	Analytical Solution of the Eddy Current Problem	144
5.4.2	Boundary Element Solution of the Eddy Current Problem	146
5.5	References	150
6	Electromagnetic Scattering Analysis	151
6.1	The Electromagnetic Wave Equations	151
6.2	Complex Phasor Form of the Wave Equations	154
6.3	Two-Dimensional Scattering from a Perfectly Conducting Cylinder of Arbitrary Cross-Section	154

6.4	Solution by the Indirect Boundary Element Method	156
6.4.1	Constant Element Case	158
6.4.2	Linear Elements Case	159
6.5	Numerical Example	159
6.6	References	162
 PART II: ANALYSIS OF THIN WIRE ANTENNAS AND SCATTERERS		 163
7	Wire Antennas and Scatterers: General Considerations	165
7.1	Frequency Domain Thin Wire Integral Equations	165
7.2	Time Domain Thin Wire Integral Equations	166
7.3	Modeling in the Frequency and Time Domain: Computational Aspects	167
7.4	References	168
8	Wire Antennas and Scatterers: Frequency Domain Analysis	171
8.1	Thin Wires in Free Space	171
8.1.1	Single Straight Wire in Free Space	172
8.1.2	Boundary Element Solution of Thin Wire Integral Equation	174
8.1.3	Calculation of the Radiated Electric Field and the Input Impedance of the Wire	180
8.1.4	Numerical Results for Thin Wire in Free Space	180
8.1.5	Coated Thin Wire Antenna in Free Space	181
8.1.6	The Near Field of a Coated Thin Wire Antenna	186
8.1.7	Boundary Element Procedures for Coated Wires	187
8.1.8	Numerical Results for Coated Wire	190
8.1.9	Thin Wire Loop Antenna	191
8.1.10	Boundary Element Solution of Loop Antenna Integral Equation	193
8.1.11	Numerical Results for a Loop Antenna	196
8.1.12	Thin Wire Array in Free Space: Horizontal Arrangement	196
8.1.13	Boundary Element Analysis of Horizontal Antenna Array	199
8.1.14	Radiated Electric Field of the Wire Array	201

8.1.15	Numerical Results for Horizontal Wire Array	201
8.1.16	Boundary Element Analysis of Vertical Antenna Array: Modeling of Radio Base Station Antennas	201
8.1.17	Numerical Procedures for Vertical Array	207
8.1.18	Numerical Results	209
8.2	Thin Wires Above a Lossy Half-Space	213
8.2.1	Single Straight Wire Above a Dissipative Half-Space	214
8.2.2	Loaded Antenna Above a Dissipative Half-Space	220
8.2.3	Electric Field and the Input Impedance of a Single Wire Above a Half-Space	222
8.2.4	Boundary Element Analysis for Single Wire Above a Real Ground	224
8.2.5	Treatment of Sommerfeld Integrals	227
8.2.6	Calculation of Electric Field and Input Impedance	229
8.2.7	Numerical Results for a Single Wire Above a Real Ground	233
8.2.8	Multiple Straight Wire Antennas Over a Lossy Half-Space	237
8.2.9	Electric Field of a Wire Array Above a Lossy Half-Space	239
8.2.10	Boundary Element Analysis of Wire Array Above a Lossy Ground	240
8.2.11	Near-Field Calculation for Wires Above Half-Space	241
8.2.12	Computational Examples for Wires Above a Lossy Half-Space	242
8.3	References	246
9	Wire Antennas and Scatterers: Time Domain Analysis	250
9.1	Thin Wires in Free Space	252
9.1.1	Single Wire in Free Space	252
9.1.2	Single Wire Far Field	256
9.1.3	Loaded Straight Thin Wire in Free Space	257
9.1.4	Two Coupled Identical Wires in Free Space	259
9.1.5	Measures for Postprocessing of Transient Response	263

9.1.6	Computational Procedures for Thin Wires in Free Space	265
9.1.7	Numerical Results for Thin Wires in Free Space	275
9.2	Thin Wires in a Presence of a Two-Media Configuration	290
9.2.1	Single Straight Wire Above a Real Ground	290
9.2.2	Far Field Equations	294
9.2.3	Loaded Straight Thin Wire Above a Lossy Half-Space	296
9.2.4	Two Coupled Horizontal Wires in a Two Media Configuration	300
9.2.5	Thin Wire Array Above a Real Ground	304
9.2.6	Computational Procedures for Horizontal Wires Above a Dielectric Half-Space	307
9.2.7	Computational Examples	317
9.3	References	333

PART III: COMPUTATIONAL MODELS IN ELECTROMAGNETIC COMPATIBILITY **335**

10	Transmission Lines of Finite Length: General Considerations	337
10.1	Transmission Line Theory Method	338
10.2	Antenna Models of the Transmission Lines	340
10.2.1	Above-Ground Transmission Lines	341
10.2.2	Below-Ground Transmission Lines	341
10.3	References	342
11	Electromagnetic Field Coupling to Overhead Lines: Frequency Domain and Time Domain Analysis	345
11.1	Frequency Domain Analysis: Derivation of Generalized Telegrapher's Equations	345
11.2	Frequency Domain Computational Results	351
11.2.1	Single Wire Above an Imperfect Ground	351
11.2.2	Multiple Wire Transmission Line Above an Imperfect Ground	355
11.3	Time Domain Analysis	359
11.4	Time Domain Computational Examples	359

11.4.1	Single Wire Transmission Line	360
11.4.2	Two Wire Transmission Line	367
11.4.3	Three Wire Transmission Line	367
11.5	References	372
12	The Electromagnetic Field Coupling to Buried Cables: Frequency- and Time-Domain Analysis	374
12.1	The Frequency-Domain Approach	374
12.1.1	Formulation in the Frequency Domain	375
12.1.2	Numerical Solution of the Integral Equation	378
12.1.3	The Calculation of Transient Response	380
12.1.4	Numerical Results	381
12.2	Time-Domain Approach	384
12.2.1	Formulation in the Time Domain	384
12.2.2	Time-Domain Energy Measures	391
12.2.3	Time-Domain Numerical Solution Procedures	392
12.2.4	Computational Examples	395
12.3	References	403
13	Simple Grounding Systems	405
13.1	Vertical Grounding Electrode	406
13.1.1	Integral Equation Formulation for the Vertical Grounding Electrode	407
13.1.2	The Evaluation of the Input Impedance Spectrum	411
13.1.3	Numerical Procedures for Vertical Grounding Electrode	413
13.1.4	Calculation of the Transient Impedance	414
13.1.5	Numerical Results	416
13.2	Horizontal Grounding Electrode	418
13.2.1	Integral Equation Formulation for the Horizontal Electrode	420
13.2.2	The Evaluation of the Input Impedance Spectrum	425
13.2.3	Numerical Procedures for Horizontal Electrode	427
13.2.4	The Transient Impedance Calculation	428
13.2.5	Numerical Results	428
13.3	Transmission Line Method Versus Antenna Theory Approach	437
13.3.1	Transmission Line Method (TLM) Approach to Modeling of Horizontal Grounding Electrode	438

13.3.2 Computational Examples	439
13.4 Measures for Quantifying the Transient Response of Grounding Electrodes	443
13.4.1 Transient Response Assessment	443
13.4.2 Measures for Quantifying the Transient Response	444
13.4.3 Computational Examples	445
13.5 References	451
14 Human Exposure to Electromagnetic Fields	453
14.1 Environmental Risk of Electromagnetic Fields: General Considerations	453
14.1.1 Nonionizing and Ionizing Radiation	454
14.1.2 Electrosmog or Radiation Pollution at Low and High Frequencies	454
14.1.3 The Effects of Low Frequency Fields	455
14.1.4 The Effects of High Frequency Fields	456
14.1.5 Remarks on Electromagnetic Fields and Related Possible Hazard to Humans	457
14.2 Assessment of Human Exposure to Electromagnetic Fields: Frequency and Time Domain Approach	458
14.2.1 Frequency Domain Cylindrical Antenna Model	458
14.2.2 Realistic Models of the Human Body for ELF Exposures	459
14.2.3 Human Exposure to Transient Electromagnetic Fields	459
14.3 Human Exposure to Extremely Low Frequency (ELF) Electromagnetic Fields	459
14.3.1 Parasitic Antenna Representation of the Human Body	460
14.3.2 Realistic Modeling of the Human Body	467
14.4 Exposure of Humans to Transient Radiation: Cylindrical Model of the Human Body	478
14.4.1 Time Domain Model of the Human Body	479
14.4.2 Measures of the Transient Response	480
14.5 References	489
Index	493