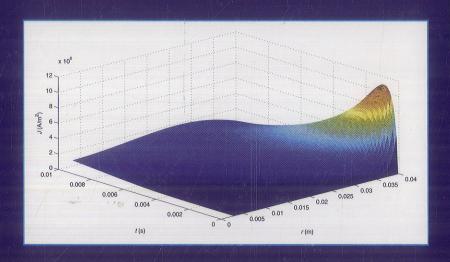
## Integral Methods in Low-Frequency Electromagnetics



IVO DOLEŽEL PAVEL KARBAN PAVEL ŠOLIN



## CONTENTS

Li	st of F	igures	÷	xi
Li	st of T	ables		xxiii
Pr	eface			xxv
Α	eknow	ledgme	nts	xxvii
1	Elec	troma	gnetic Fields and their Basic Characteristics	1
	1.1	Funda	amentals	1
		1.1.1	Maxwell's equations in integral form	2
		1.1.2	Maxwell's equations in differential form	3
		1.1.3	Constitutive relations and equation of continuity	3
		1.1.4	Media and their characteristics	4
		1.1.5	Conductors	4
		1.1.6	Dielectrics	5
		1.1.7	Magnetic materials	5
		1.1.8	Conditions on interfaces	6
1.2 Potentials		Poten	tials	1 1 2 3 3 4 4 2 5 6 8 8 8
		1.2.1	Scalar electric potential	8
		1.2.2	Magnetic vector potential	9
		1.2.3	Magnetic scalar potential	10
	1.3	Mathe	ematical models of electromagnetic fields	10
				_

		1.3.1	Static electric field	10	
		1.3.2	Static magnetic field	12	
		1.3.3	Quasistationary electromagnetic field	14	
		1.3.4	General electromagnetic field	15	
	1.4		and forces in electromagnetic fields	16	
		1.4.1	Energy of electric field	17	
		1.4.2	Energy of magnetic field	18	
		1.4.3	Forces in electric field	19	
		1.4.4	Forces in magnetic field	23	
	1.5	Power	balance in electromagnetic fields	24	
		1.5.1	Energy in electromagnetic field and its transformation	24	
		1.5.2	Balance of power in linear electromagnetic field	24	
2	Ove	rview	of Solution Methods	27	
	2.1	Conti	nuous models in electromagnetism	27	
		2.1.1	Differential models	28	
		2.1.2	Integral and integrodifferential models	31	
	2.2		ods of solution of the continuous models	32	
		2.2.1	Analytical methods	33	
		2.2.2	Numerical methods	33	
		2.2.3	Methods based on the stochastic approach	33	
		2.2.4	Specific methods	34	
	2.3	Class	ification of the analytical methods	34	
		2.3.1	Methods built on the basic laws of electromagnetics	34	
		2.3.2	Methods based on various transforms	35	
		2.3.3	Direct solution of the field equations	43 46	
	2.4	Numerical methods and their classification			
	2.5	Diffe	rential methods	48	
		2.5.1	Difference methods	48	
		2.5.2	Weighted residual methods	53	
		2.5.3	Variational and other related methods	58	
	2.6	Finite	e element method	62	
		2.6.1		60	
			approximate functions	63	
		2.6.2		73	
		2.6.3		76	
	2.7		ral and integrodifferential methods	76	
	2.8	Impo	ortant mathematical aspects of numerical methods	76	
		2.8.1	•	77	
		2.8.2	-	78 78	
		2.8.3		78	
	2.9	Nun	nerical schemes for parabolic equations	78	

		CONTENTS	vií
	2.9.1	Explicit scheme	79
	2.9.2	Implicit scheme	80
Soli	ution of	f Electromagnetic Fields by Integral Expressions	83
3.1	Introd	uction	83
3.2		regration area	84
3.2	3.2.1	Review of typical problems	84
	3.2.2	Electric field generated by a solitary filamentary conductor of	
	• . • . •	infinite length	84
	3.2.3	Electric field of charged thin circular ring	85
	3.2.4	Magnetic field generated by a solitary filamentary conductor of	
		infinite length	88
	3.2.5	Magnetic field of thin circular current carrying loop	90
	3.2.6	Electric field generated by a system of uniformly charged parallel	
		thin filaments of infinite length	93
	3.2.7	Magnetic field generated by a system of currents carrying parallel	
		filamentary conductors of infinite length	96
3.3	2D in	tegration area	97
	3.3.1	Review of typical problems	97
	3.3.2	Magnetic field of an infinitely long massive conductor carrying	
		DC current	97
	3.3.3	Magnetic field of a massive ring of rectangular cross section	101
3.4	Force	s acting in the system of long massive conductors	106
	3.4.1	Self-inductance of a massive ring of rectangular cross section	110
	3.4.2	Radial force on a massive ring of rectangular cross section	115
	3.4.3	Cylindrical air-core coils and their parameters	118
	3.4.4	Electric field of an idealized thundercloud	128
3.5	3D in	tegration area	133
	3,5.1	Review of typical problems	133
	3.5.2	Magnetic field around a helicoidal air-core coil	133
Inte	egral aı	nd Integrodifferential Methods	145
4.1	Integ	ral versus differential models	145
4.2	Theo	retical foundations	149
	4.2.1	Electrostatic fields produced by charged bodies	149
	4.2.2	Eddy currents in linear homogeneous systems	150
	4.2.3	Planar and axisymmetric arrangements	153
4.3	Static	and harmonic problems in one dimension	156
	4.3.1	Electric field of a thin charged circular ring	156
	4.3.2	Current density in a harmonic current carrying massive hollow	
		conductor	159

		4.3.3	Current density in a system consisting of a harmonic current	
			carrying massive hollow cylindrical conductor—a coaxial	
			shielding pipe	165
	4.4	Static a	and harmonic problems in two dimensions	170
		4.4.1	Electric field of a thin rectangular plate	171
		4.4.2	Electric field of a charged cylinder	174
		4.4.3	Harmonic currents in a long conductor of arbitrary cross section	180
	4.5	Static	problems in three dimensions	185
		4.5.1	Electric field of two charged cubes	186
		4.5.2	Electric field of two charged plates	191
	4.6	Time-dependent eddy current problems in one dimension and two		
		dimensions		191
		4.6.1	Massive conductor carrying time-dependent current	192
		4.6.2	Pulse current in a long conductor of rectangular profile	200
		4.6.3	Short-circuit effects in a three-phase system	204
	4.7	Static	and 2D eddy current problems with motion	206
		4.7.1	Distribution of charge in a system of two moving conductors	207
5	Indi	rect Sc	olution of Electromagnetic Fields by the Boundary Elemen	t
	Method			217
	5.1	Introd	luction	217
		5.1.1	Fundamental concepts	219
		5.1.2	Green's functions of common differential operators	224
	5.2	.2 BEM-based solution of differential equations		226
		5.2.1 Particular steps of the solution		226
		5.2.2	Illustrative example in one dimension	227
		5.2.3	Multidimensional problems	230
	5.3	Probl	ems with 1D integration area	230
		5.3.1	Two eccentrically placed charged cylinders	231
		5.3.2	Magnetic field in the air gap of a rotating machine	234
		5.3.3	Electric field near a high-voltage three-phase line	239
		5.3.4	Magnetic field of a massive conductor above a ferromagnetic plate	241
				0.45
6	Inte	egral E	quations in Solution of Selected Coupled Problems	245
	6.1	Cont	inual induction heating of nonferrous cylindrical bodies	245
		6.1.1	Introduction	245
		6.1.2		246
		6.1.3	Mathematical model and its solution	246
		6.1.4	Illustrative example	247
		615	Conclusion	255

ίx

	6.2	Induction heating of a long nonmagnetic cylindrical billet rotating in a			
	0.2		m magnetic field	255	
		6.2.1	Introduction	255	
		6.2.2	Formulation of the technical problem	256	
		6.2.3	Continuous mathematical model of the problem	256	
		6.2.4	Example of computation	261	
		6.2.5	Conclusion	266	
	6.3	Pulsed	Induction Accelerator	266	
		6.3.1	Introduction	266	
		6.3.2	Formulation of the problem	268	
		6.3.3	Continuous mathematical model	269	
		6.3.4	Discretized model and its numerical solution	273	
		6.3.5	Example of calculation	274	
7	Nun	nerical	Methods for Integral Equations	281	
	7.1	Introd	uction	281	
		7.1.1	Model problem	281	
		7,1.2	Projection methods	282	
	7.2	Colloc	cation methods	283	
		7.2.1	Optimal collocation points in one dimension	285	
		7.2.2	Optimal basis functions in one dimension	285	
		7.2.3	Efficient assembly of the collocation matrix	288	
		7.2.4	Optimal collocation points in two dimensions	289	
		7.2.5	Transformation of points from reference to physical elements	289	
		7.2.6	Optimal basis functions in two dimensions	292	
		7.2.7	Efficient assembly of the collocation matrix	293	
	7.3	Galer	kin methods	293	
		7.3.1	Schur complement method for partially orthonormal basis	296	
	7.4	Nume	erical example	296	
		7.4.1	Basic features of the proposed higher-order technique	297	
		7.4.2	Illustrative example	298	
Α	ppen	dix A:	Basic Mathematical Tools	301	
	<b>A</b> .1	Vecto	rs, matrices, and systems of linear equations	301	
		A.1.1	Vectors	301	
		A.1.2	Matrices	304	
		A.1.3		306	
		A.1.4	-	310	
	A.2		or analysis	311	
		A.2.1	Differential and integral operations with vectors in Cartesian		
			coordinates	311	

7

Topic Index

	A.2.2	Other orthogonal coordinate systems	315
Appen	díx B: S	Special Functions	319
B.1	Bessel	functions	319
	B.1.1	Bessel functions of the first kind	320
	B.1.2	Bessel functions of the second kind	321
	B.1.3	Hankel functions	321
	B.1.4	Modified Bessel functions	322
	B.1.5	Asymptotic forms of Bessel functions	322
	B.1.6	Some other useful relations	324
	B.1.7	Computation of Bessel and other related functions	324
B.2	Ellipti	c integrals	325
	B.2.1	Incomplete and complete elliptic integrals of the first kind	325
	B.2.2	Incomplete and complete elliptic integrals of the second kind	325
	B.2.3	Incomplete and complete elliptic integrals of the third kind	326
	B.2.4	Some other useful formulas	328
B.3	Specia	d polynomials	329
	B.3.1	Legendre polynomials of the first kind	329
	B.3.2	Chebyshev polynomials of the first kind	330
Appen	dix C: I	ntegration Techniques	333
C.1	Analy	tical calculations of some integrals over typical elements	333
	C.1.1	Rectangle	334
	C.1.2	Triangle	338
	C.1.3	A ring of rectangular cross section	344
	C.1.4	A brick	345
C.2	Techn	iques of numerical integration	346
	C.2.1	Numerical integration in one dimension	347
	C.2.2	Numerical integration in two dimensions	355
	C.2.3	Numerical integration in three dimensions	365
	Refere	ences	375

385