

Index

- ABC finite elements, 225–227
- AC currents, 107, 169, 179–181
- Accumulators, 274
- Acoustics, 274
- Actuator(s), magnetic, *see also* Magnetic actuators
 - acceleration of, 125–127
 - definition of, 3, 85
 - finite element analysis of, 45, *see also* Maxwell SV
 - force of, *see* Magnetic force
 - high speed, 195
 - reciprocating, 239
 - size of, 125–127
- Airgap, 29, 32–35, 267
- Alternator load dump, 210
- Ampere’s Law, 12–14, 29–32
- Analogy(ies), 247, 250–251, 273–277
- Apertures, 210–215
- Architecture of VHDL-AMS models, 254–257
- Armature, 34, 85
- Autocad DXF file, 203
- Automotive brakes and control, 157–158, 271–272
- Automotive sensors, 157–159, 165, 186
- Axisymmetric geometry, 52–53

- Bessel function(s), 118, 131
- Bessho DC solenoid
 - flux plot of, 235
 - geometry, 52–54
 - transient operation, 127, 131–139, 195, 234–238, 251–254, 266–268, 279–296
- Bit, 168
- Block diagram, 4–6, 252, 258–263
- Boundary conditions, 45
- Brake(s), 103, 271–272

- Cable, coaxial, 216
- CAN bus, 186
- Can, 212–215
- Capacitance, 75–77, 109–111
- Capacitor, 23–26, 109–111
- Chambers, absorption, 215
- Chambers, test, 215–220
- Chopper circuit, 280–283, *see also* Pulse-width modulated
- Circuit breakers, 4
- Circulation, 10, 13
- Clapper armature actuator, 196–198, 248, *see also* Eaton AC solenoid
- Closure time, 236–238, 240–241, 248–249, 253, 277–297
- Clutches, 103
- CMOS, 146
- Coenergy, 56–57
- Coil(s)
 - ampere-turns, 13
 - design, 191–206
 - resistance, 172–173, 191–199
 - sensor, 158–159, 165–167, 179–181
 - time constant, 194–195
 - voltage induced, 19
- Common-mode noise, 210
- Complex AC circuit methods, 110–111
- Complex-plane impedance, 169–173
- Composite materials, 21
- Computational fluid dynamics (CFD), 274
- Conductivity
 - electrical, 20
 - temperature effect on, 192
 - tensor electrical, 146–150, 224
 - thermal, 199
- Contactors, 4, *see also* Eaton AC solenoid
- Continuity, 25
- Contours, 51–53, 219–220

302 INDEX

- Control system, 6, 258, *see also* Feedback control
- Control System Toolbox for MATLAB, 258
- Controller, 254
- Coordinates, rectangular (Cartesian), 7
- Core loss
 - curves, 109
 - equation, 203
- Corrosion cracks, 174
- Cosimulation, 264
- Coupled electromagnetic
 - analysis, 209–220, 224
 - fields, 25
 - radiation, 209–220
- Coupling electric circuits to finite elements, 225–232
- Coupling, antiferromagnetic, 160
- Cramer's rule, 149
- Curl, 9–12
- Current, 12–14
 - density, 12–14, 193
 - dip, 236–237, 248–249
 - in plane (CIP), 160
 - perpendicular to plane (CPP), 160
 - waveform, 226–231, 236–240
- Cyclotron frequency, 147
- Cylinders, hydraulic, 283–296

- dB, 212–213
- DC coils, 191–193
- Deadbands, 100
- Del operator, 7
- Delay time, 292, *see also* Diffusion time
- Demagnetization curve, 63–64
- Dependent sources, 278–279
- Design optimization methods, 92
- Determinant, 9–10
- Diffusion time, 125, 128–142, 264–268, 202–296
- Digital solver, 254
- Diode, flyback, 280
- Discretization, 39
- Disk drives, 5–6, 97, 160–162, 167–169, *see also* Recording heads and Voice coil actuators
- Displacement current, 25–26
- Displacement (mechanical), 232, 260
- Dither, 101
- Divergence, 9–11

- Eaton AC solenoid
 - flux plot of, 52
 - geometry of, 45
 - shading ring in, 115
 - transient analysis of, 238–341
- Eddy axial formulation, 117–118
- Eddy current(s)
 - braking, 174
 - coefficient, 203
 - effects, 20–22, 195–199, 203, *see also* Diffusion time
 - moving, 173–174
 - resistor, 264–268, 292–296
 - sensors, 169–174
 - stationary, 170–173
- Electric
 - charge density, 23
 - circuit, 225–226
 - field, motional, 20, 235–240, 248–250
 - field intensity, 19
 - flux density, 22–23
 - scalar potential, 22–24, 224
- Electrode(s), 145–148, 150–158
- Electrohydraulic analysis, 271–296
- Electromagnetic compatibility (EMC), 209–220
- Electromagnetic interference (EMI), 209–220
- Electromagnetic problem types, 225
- Electromagnetics, 7–28
- Electromagnets, 64
- Electromechanical analysis, 223–297
- Electronics module, 176, 178
- Electron(s), 146–147
- Electrostatic fields, 200–201, 218–220
- Electrostatic scalar potential, 22, 224
- Emissions, conducted, 209–210
- Emissions, radiated, 209–215
- Energy
 - conservation, 39–40
 - conversion, 3–4, 272
 - density, 56
 - functional, 39–41
 - input, 39–40
 - loss, 195, *see also* Power loss
 - stored, 39–40, 56–57, 218–220
- Entity in VHDL-AMS models, 254, 257
- Equivalent circuits, 109–111

- Excitation vector, 42, 224, 232
Excitations, 45
- Faraday's Law, 18–22, 165–168, 210, 228, 251
- Feedback control, 6, 158, 168, 272, 291
- Fermi gas theory, 146–149
- Ferrite(s), 21, 36, 63–64, 196–199
- Ferrofluids, 98
- Ferromagnetic layers, 160
- Ferromagnetics, 15–18
- Film coefficient, 201
- Filtering, 209–210
- Finite difference method, 39
- Finite element(s)
 axisymmetric, 52–53, 226
 edge, 43
 model, 44–48
 nodes, 41
 first order, 41–42
 open boundary, 45, 226–227
 quadratic shape function, 43
 tangential vector, 43
 triangular, 41–44
- Finite-element analysis, *see also* Maxwell SV
 acoustic, 274
 electric conduction, 149–158, 161–162
 electromechanical, 223–245
 fluid(s), 202, 274
 magnetic, 39–49, 223–229
 parametric, 89, 92, 249–250, 286
 structural, 226–241
 thermal, 199–206
- Flow force, 279–296
- Flow, hydraulic, 273–295
- Flowmeters, 291
- Fluid dynamics, 39, 274
- Fluid power systems, 274–296
- Flux
 fringing, 33, 36, 55–56
 leakage, 55–56, 205
 lines, 218–220
 linkage, 20, 69–70, 250
 partial, 55–56
- Flux density plots, 53
- Flux gate sensors, 179–186
- Force(s)
 bi-directional, 96–98
 distribution, 226–241
 integration, 232–234
 magnetic, *see* Magnetic force
 on capacitor, 76
 pulsations, 113–116
 repulsive, 115
- Frequency, resonant, 110
- Friction, 101, 252, 260
- Fringing factor, 36
- Functional minimization, 40–42
- Galerkin's method, 43
- Gasket, 211–212
- Gradient, 7–9
- Hall effect sensors, 145–159
- Hard-disk drives, *see* Disk drives
- Hardware Description Language (HDL), 254
- Heat, 199–206
- Holes, 146
- Hydraulic(s), 271–296
 capacitance, 273–274, 277–283
 cylinders, 283–296
 inductance, 273–274
 line(s), 272–273
 pressure(s), 271–296
 resistor (orifice), 273–296
 systems, 271–296
- Hysteresis, 108–109, 168
 coefficient, 203
 loss, 108–109
- Impedance, 77–80, 169–174, 194–199
 characteristic, 216
 Thevenin, 216
- Inductance, 72–74, 194–199, 202–204, 247–251
 end turn, 239–240
 incremental, 73
 matrix, 72–74
 mutual, 72
 secant, 73
 self, 72
- Inductive kick, 242–244
- Inductor(s), 72, 202–206
 leakage, 266–267
 rectangular, 133–135, 140–142
- Injectors, fuel, 3, 292

304 INDEX

- Insulation, glastic, 200–201, 204
- Integrated circuits, 146
- Inverse problem, 171–172
- Iron (Fe), 15–17
- Iron filings, 51

- Kirchhoff's Current Law, 9, 226
- Knee, 17

- Laminar orifice(s), 274
- Laminated steel, 108–109
- Laminations, 21
- Laplace transform s domain, 258–263
- Latching switches, 242
- Leakage flux, 55–56, 205
- Levitation, 115
- Light, speed of, 211
- Line segments, 29
- Linear actuators, 85–101
- Linear time invariant (LTI), 260
- Linear variable differential transformers (LVDTs), 174–177, 292
- Lines of force, 51
- Locus, impedance, 171
- Lorentz force, 62, 96–97, 259
- Losses, *see* Power loss
- Loudspeakers, 3, 96

- Machines, rotary, 85, 101–103
- Magnet, lifting, 112–113
- Magnetic
 - AC actuators, 107–123, 238–241, *see also* Eaton AC solenoid
 - bearings, 102–103
 - brakes and clutches, 103, 174
 - constant force actuator, 99–100
 - couplings, 103
 - DC actuators, 85–106, 234–238, 248–268, 271, *see also* Bessho DC solenoid
 - diffusion time, linear, 128–132
 - diffusion time, nonlinear, 132–142
 - domains, 15
 - energy, 40–42, 56–57
 - field, 7
 - field intensity, 12
 - flux, 13, 69–70
 - flux density, 12
 - flux line plots, 51–53
 - force, 3, 51–68, 74–75, 86–101, 113–116, 125–129, 232–234, 251–261
 - materials, 15–18
 - performance parameters, 69–81
 - pole, 32
 - pressure, 60–61, 232–233, 271
 - Resonance Imaging (MRI), 181
 - Reynolds number, 173
 - sensors, 145–186, 272, 291
 - sensors, inductive, 165–177, 210–211
 - separator, 98
 - switches, 241–242
 - torque, 66–67
 - vector potential, 24, 224
- Magnetizing fixtures, 168
- Magnetoimpedance (MI) sensors, 182–186
- Magnetometers, 181
- Magnetomotive force (MMF), 31
- Magnetostriction (MR), 152–162
 - classical, 152–156, 159–162
 - colossal (CMR), 160
 - extraordinary (EMR), 161
 - giant (GMR), 160
 - tunneling (TMR), 160
- Magnetostrictive heads, 161–162
- Magnetostrictive sensors, 159–162, 242
- Magnetostatics, 39–42
- Magnetostriction, 177–179
- Magnetostrictive materials, 97
- Magnetostrictive sensors, 177–179
- Magnets, permanent, 62–66
- Material
 - anisotropic, 16
 - hard magnetic, 17
 - isotropic, 16
 - soft magnetic, 15
- MATLAB, 258–263
- Matrix
 - conductance, 223–224
 - damping, 231–232
 - equation, 42–44, 223–232
 - mass, 231–232
 - permittance, 223–224
 - reluctance, 42, 223–224
 - solution sparsity, 44
 - stiffness, 42, 231–232
- Maxwell stress tensor, 61, 232–233

- Maxwell® SV (Student Version) finite element software numbered examples
- chapter 4, 46–49
 - chapter 5, 55–56, 59–60, 65–66
 - chapter 6, 70, 73–74, 76–77, 78–80
 - chapter 7, 88–89, 89–91, 93–94, 94–96
 - chapter 8, 112–113, 115–116, 120–122
 - chapter 9, 129–131, 133–135, 137–142
 - chapter 10, 152–155
 - chapter 11, 168–169, 172–173, 176–177
 - chapter 12, 196, 196–199, 200–201
 - chapter 13, 212–215, 219–220
- Maxwell, James Clerk, 24–26
- Mechanical input, 271–272
- Mechanical stress, 39, 240–241
- Mechatronics, 6
- Metal detectors, 169
- Micro-electromechanical systems (MEMs), 161
- Microphone, 5, 167
- Midnode variables, 43
- Model validation, 53–54
- Modulus of elasticity, 233–234, 239
- MOSFETs, 181
- Motes, 186
- Motion control, 3
- Motional EMF effects, 235–238, 248–250
- Motors, 4, *see also* Step motors
- Moving surfaces, 231
- Multisim software, 247
- Nanoparticles, 182
- Nanotechnology, 15, 161
- Newton's iterative method, 43
- Newton's Law(s), 231–232, 251, 286
- Nodes, 41, 224–226, 231–232, 256
- Noise, 209–210
 - common-mode, 210
 - radiated, 209–220
- Non-destructive evaluation (NDE), 171–172
- Non-destructive testing (NDT), 172
- Nonlinear B - H curve, 17–18, *see also* Saturation
- Nonsinusoidal waveforms, 111
- Normal AC B - H curves, 109
- Nuclear power plants, 174
- Ohm's Law, 20
- Orifice, hydraulic, 274
- Orifice, variable, 273–274, *see also* Valve(s)
- Overshoot, percent (P.O.), 260–263
- Package body, 254
- Packing factor, 192–193
- Parametric finite element analysis, 89–90, 92, 249–250
- Path, closed, 13, 29–31
- Performance parameters, 69–81
- Permanent magnet, moving, 167
- Permanent magnet(s)
 - latch, 242
 - modeling, 224
 - properties, 62–66
 - sensors, 158
- Permeability, 12, 15
 - complex, 212
 - effective, 111
 - incremental, 17
 - relative, 15
 - tensor, 16
- Permeance, 31
- Permittivity, 23, 200–201, 212, 216–218
- Phase angle, 194
- Pickup coils, 291, *see also* Coil(s), sensor
- Pig (traveling sensor), 174
- Pins, 256
- Pipe, 174
- Plastics, 216
- Plug and play, 186
- Plunger armature, 91–96, 126–127, 131–132, 137–138, *see also* Bessho DC solenoid
- Pneumatic systems, 274
- Poisson's differential equation, 199–200
- Poisson's ratio, 234, 239
- Polynomial order p , 43
- Position versus time, *see* Bessho DC solenoid *and* Eaton AC solenoid
- Postprocessing, 51
- Potentials, 22–24
- Power loss(es), 108–113, 195–203, *see also* Eddy current effects
- Preprocessing, 46
- Pressure
 - hydraulic, 271–296

306 INDEX

- Pressure (*continued*)
 magnetic, 60–61, 232–233
 versus flow curves, 274, 286–287
- Primary winding, 175–176, 227–228, 242–244
- Proportional actuators, 98–101
- Prosthesis, 3
- Proximity effects in coil wires, 195–199
- Proximity sensors, 169–173
- Pull curve, 86–90
- Pulse, interrogation, 178
- Pulse-width modulated (PWM), 100–101, 280–283, 290–292
- Pump(s), 273–296
- Reactance, 78–79
- Reciprocating magnetic actuators, 239, 273
- Recording heads, *see also* Disk drives
 inductive, 167–169
 magnetoresistive, 160–162
- Reduced order model, 260–263
- Reed switches, 241
- Reflections, 216
- Relaxation techniques, 39
- Relay(s), 238–241
- Reluctance, 30–37
 AC complex, 36, 119–123
 force, 58
 method, 29–37
 method, limitations of, 37
- Reluctivity tensor, 224
- Remanent (residual) flux density, 63–64
- Resistance, 148, 191–199
- Resistivity, 149
- Resistor, eddy current (magnetic) diffusion, 264–268, 292–296
- Resonant frequency, natural, 110
- Right hand rule, 16
- Rigid armature motion analogies, 251
- Rigid body motion, 228–231, 250–251
- Ripple, *see* Pulse-width modulated
- Robot(s), 3, 170
- Roots function of MATLAB, 260–262
- Rotary actuators, 101–103
- Saturation, 17, 56–61, 228–231, 242–244
- Scalar(s), 7
- Secondary winding, 175–177, 227–228, 242–244
- Security systems, 169
- Seek time, 97, 168
- Semiconductors, 145–146
- Sensor(s), *see also* Magnetic sensors
 Hall effect, 5, 145–159
 LVDT, 291
 magnetostrictive, 177–179, 291
 output voltage, 158–159
 proximity, 5, 169–173
 toothed armature, 34
 velocity, 5–6, 165–167, 210
- Shading coil, 114
- Shading ring, 114–115
- Shape functions, 41, 43, 224
- Shields, 210–215
- Signal-to-noise ratio, 209–210
- Signals, 209–210
- Simplorer software, 180–181, 252–256, 278, 281
 models of electrohydraulics, 283–285, 292–293
 models of electromechanics, 256–258, 264–268
- Simulink, 258–259
- Skin depth, 107–108
- Skin effect, 112–113, 196–199, 210–214
- Smart dust, 186
- Smart sensors, 186
- Soft adjacent layers (SALs), 160
- Software
 finite element, 46, 223–245, *see also* Maxwell SV
 systems, 247–268
- Solenoid actuators, 85–96
 clapper armature, 85–91, *see also* Eaton AC solenoid
 plunger armature, 91–96, *see also* Bessho DC solenoid
- Solenoidal coil, 85
- Sources, *see* Excitations
- Speed sensors, 157–159, 165–167
- Speed voltage, 248–250, *see also* Motional EMF effects
- SPICE, 180–181, 247, 274
 models of electrohydraulics, 278–296
 models of electromechanics, 248–249, 248–250
 models of hydraulics, 275, 275–277, 277–278

- Spring, nonlinear, 238–239
- SQUID magnetometers, 181
- Stage, hydraulic, 272
- Stator, 34, 85
- Steel, *see also* Laminated steel
 - B-H* relation, 15–18
 - cuts, 120–123
 - cylinder, 131–132, 135–139
 - slab, 129–131, 132–135
 - solid, 111–113
- Step *B-H* curve, 132–139
- Step motor(s), 101–103
- Stiction, 101
- Stiffness matrix, 42, 231
- Stokes' law, 13
- Strain, mechanical, 177–178, 240–242
- Stress, mechanical, 177–178, 231, 240–242, *see also* Maxwell stress tensor
- Stripe, magnetoresistive, 161
- Stroke time, 125–127, 234–238, 240–241, *see also* Closure time
- Superconductors, 64
- Surface, closed, 13
- Susceptance, conducted, 209–210
- Susceptance, radiated, 209–210
- Switch, electronic, 280, *see also* Pulse-width modulated
- Switched reluctance motors, 102
- Switches, *see* Magnetic switches *and* Reed switches
- Switchgear, 4
- System(s)
 - models, 247–269
 - second order, 260–263
 - software, *see* MATLAB, Simulink, *and* Simplorer
 - third order, 260–263
- Table, flux linkage, 249–250
- Table, force, 249–250
- Tank, hydraulic, 273
- Target, 170–173
- TEM transmission lines, 215–217
- TEM cells, 217
- Temperature, 191–192, 199–206
- Terfenol, 178
- Tesla, 12
- Tetrahedrons, 43, 226
- Thermal
 - analysis, 39, 199–206
 - conduction, 199–201
 - convection, forced, 201–202
 - convection, free, 201–206
 - radiation, 201–206
- Time constant, 194, *see also* Diffusion time
- Time, *see also* Closure time
 - peak, 260–263
 - rise, 260–263
 - settling, 260–263
- Timeline of actuator operation, 125
- Timestepping, 232–244, 252, 264, *see also* Simplorer *and* SPICE
- Toolboxes for MATLAB, 258
- Tooth pitch, 159
- Toothed wheel sensors, 157–159, 165–167
- Torque sensing, 179
- Torquers, 101
- Transducer(s), 85, 261
- Transfer function, 260–263
- Transformers, 21, 227–231, 242–244
- Transformers, linear variable differential, 5, 174–177
- Transient operation of actuators, 125–142
- Translation, mechanical, 232
- Transmission lines, 215–217
- Tri-plate cells, 217–220
- Turbulent orifices, 273–274
- Turnoff, 128–130
- Turnon, 128–142
- Turns, 13
- Units
 - centimeter-gram-second (CGS), 17
 - SI (meter-kilogram-second), 299–300
- Valve(s)
 - control, 274, 283–291
 - electrohydraulic, 272, 278–296
 - four-way, 283–291
 - hydraulic, 272–274, 278–296
 - lands in, 285
 - spool, 285
- Variable reluctance sensor, 157–159, 165–167
- Variables, across, 256
- Variables, through, 256
- Vector, unknown, 42, 224, 231–232
- Vectors, 7

308 INDEX

VHDL-AMS, 254–258

View factors, 202

Virtual work, 57–59

Voice coil actuators, 96–97

 MATLAB model of, 259–263

Voltage

 induced, 19–20

 potential, 22

 read head, 167–169

 step, 194

Wavefront, 132

Waveguide, acoustic, 178–179

Wavelength, 211

Waves, 215–216

Wheel, toothed, 157–160

Wire diameter, 192–193

Wire gauge, 192

Zigbee, 186