# Contents

Preface ix

**PART I MAGNETICS** 1

1. Introduction 3
   1.1 Overview of Magnetic Actuators 3
   1.2 Overview of Magnetic Sensors 4
   1.3 Actuators and Sensors in Motion Control Systems 5
   References 6

2. Basic Electromagnetics 7
   2.1 Vectors 7
      2.1.1 Gradient 7
      2.1.2 Divergence 9
      2.1.3 Curl 9
   2.2 Ampere’s Law 12
   2.3 Magnetic Materials 15
   2.4 Faraday’s Law 18
   2.5 Potentials 22
   2.6 Maxwell’s Equations 24
   Problems 26
   References 28

3. Reluctance Method 29
   3.1 Simplifying Ampere’s Law 29
   3.2 Applications 32
   3.3 Fringing Flux 36
   3.4 Complex Reluctance 36
   3.5 Limitations 37
   Problems 37
   References 37
4. Finite-Element Method

4.1 Energy Conservation and Functional Minimization
4.2 Triangular Elements for Magnetostatics
4.3 Matrix Equation
4.4 Finite-Element Models
Problems
References

5. Magnetic Force

5.1 Magnetic Flux Line Plots
5.2 Magnetic Energy
5.3 Magnetic Force on Steel
5.4 Magnetic Pressure on Steel
5.5 Lorentz Force
5.6 Permanent Magnets
5.7 Magnetic Torque
Problems
References

6. Other Magnetic Performance Parameters

6.1 Magnetic Flux and Flux Linkage
   6.1.1 Definition and Evaluation
   6.1.2 Relation to Force and Other Parameters
6.2 Inductance
   6.2.1 Definition and Evaluation
   6.2.2 Relation to Force and Other Parameters
6.3 Capacitance
   6.3.1 Definition
   6.3.2 Relation to Energy and Force
6.4 Impedance
Problems
References

PART II ACTUATORS

7. Magnetic Actuators Operated by Direct Current

7.1 Solenoid Actuators
   7.1.1 Clapper Armature
   7.1.2 Plunger Armature
7.2 Voice Coil Actuators
7.3 Other Actuators Using Coils and Permanent Magnets
7.4 Proportional Actuators
7.5 Rotary Actuators
Problems
References

8. Magnetic Actuators Operated by Alternating Current

8.1 Skin Depth
8.2 Power Losses in Steel
  8.2.1 Laminated Steel
  8.2.2 Equivalent Circuit
  8.2.3 Solid Steel
8.3 Force Pulsations
  8.3.1 Force with Single AC Coil
  8.3.2 Force with Added Shading Coil
8.4 Cuts in Steel
  8.4.1 Special Finite-Element Formulation
  8.4.2 Loss and Reluctance Computations

Problems
References

9. Magnetic Actuator Transient Operation

9.1 Basic Timeline
9.2 Size, Force, and Acceleration
9.3 Linear Magnetic Diffusion Times
  9.3.1 Steel Slab Turnon and Turnoff
  9.3.2 Steel Cylinder
9.4 Nonlinear Magnetic Diffusion Time
  9.4.1 Simple Equation for Steel Slab with “Step” B–H
  9.4.2 Transient Finite-Element Computations for Steel Slabs
  9.4.3 Simple Equation for Steel Cylinder with “Step” B–H
  9.4.4 Transient Finite-Element Computations for Steel Cylinders

Problems
References

PART III SENSORS

10. Hall Effect and Magnetoresistive Sensors

10.1 Simple Hall Voltage Equation
10.2 Hall Effect Conductivity Tensor
10.3 Finite-Element Computation of Hall Fields
  10.3.1 Unsymmetric Matrix Equation
  10.3.2 2D Results
  10.3.3 3D Results
10.4 Toothed Wheel Hall Sensors for Position 157
10.5 Magnetoresistance 159
  10.5.1 Classical Magnetoresistance 159
  10.5.2 Giant Magnetoresistance 160
  10.5.3 Newest Forms of Magnetoresistance 160
10.6 Magnetoresistive Heads for Hard-Disk Drives 161
Problems 162
References 162

11. Other Magnetic Sensors 165
11.1 Speed Sensors Based on Faraday’s Law 165
11.2 Inductive Recording Heads 167
11.3 Proximity Sensors Using Impedance 169
  11.3.1 Stationary Eddy Current Sensors 170
  11.3.2 Moving Eddy Current Sensors 173
11.4 Linear Variable Differential Transformers 174
11.5 Magnetostrictive Sensors 177
11.6 Flux Gate Sensors 179
11.7 Magnetometers and Motes 181
Problems 186
References 186

PART IV  SYSTEMS 189

12. Coil Design and Temperature Calculations 191
12.1 Wire Size Determination for DC Currents 191
12.2 Coil Time Constant and Impedance 194
12.3 Skin Effects and Proximity Effects for AC Currents 195
12.4 Finite-Element Computations of Temperatures 199
  12.4.1 Thermal Conduction 199
  12.4.2 Thermal Convection and Thermal Radiation 201
  12.4.3 AC Magnetic Device Cooled by Conduction, Convection, 202
               and Radiation
Problems 206
References 206

13. Electromagnetic Compatibility 209
13.1 Signal-to-Noise Ratio 209
13.2 Shields and Apertures 210
13.3 Test Chambers 215
  13.3.1 TEM Transmission Lines 215
### CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.3.2</td>
<td>TEM Cells</td>
<td>217</td>
</tr>
<tr>
<td>13.3.3</td>
<td>Triplate Cells</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>220</td>
</tr>
<tr>
<td>14.</td>
<td>Electromechanical Finite Elements</td>
<td>223</td>
</tr>
<tr>
<td>14.1</td>
<td>Electromagnetic Finite-Element Matrix Equation</td>
<td>223</td>
</tr>
<tr>
<td>14.2</td>
<td>0D and 1D Finite Elements for Coupling Electric Circuits</td>
<td>225</td>
</tr>
<tr>
<td>14.3</td>
<td>Structural Finite-Element Matrix Equation</td>
<td>228</td>
</tr>
<tr>
<td>14.4</td>
<td>Force and Motion Computation by Timestepping</td>
<td>232</td>
</tr>
<tr>
<td>14.5</td>
<td>Typical Electromechanical Applications</td>
<td>234</td>
</tr>
<tr>
<td>14.5.1</td>
<td>DC Solenoid with Slowly Rising Input Current</td>
<td>234</td>
</tr>
<tr>
<td>14.5.2</td>
<td>DC Solenoid with Step Input Voltage</td>
<td>235</td>
</tr>
<tr>
<td>14.5.3</td>
<td>AC Clapper Solenoid Motion and Stress</td>
<td>238</td>
</tr>
<tr>
<td>14.5.4</td>
<td>Transformers with Switches or Sensors</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>244</td>
</tr>
<tr>
<td>15.</td>
<td>Electromechanical Analysis Using Systems Models</td>
<td>247</td>
</tr>
<tr>
<td>15.1</td>
<td>Electric Circuit Models of Magnetic Devices</td>
<td>247</td>
</tr>
<tr>
<td>15.1.1</td>
<td>Electric Circuit Software Including SPICE</td>
<td>247</td>
</tr>
<tr>
<td>15.1.2</td>
<td>Simple LR Circuits</td>
<td>247</td>
</tr>
<tr>
<td>15.1.3</td>
<td>Tables of Nonlinear Flux Linkage and Force</td>
<td>249</td>
</tr>
<tr>
<td>15.1.4</td>
<td>Analogies for Rigid Armature Motion</td>
<td>250</td>
</tr>
<tr>
<td>15.1.5</td>
<td>Maxwell SPICE Model of Bessho Actuator</td>
<td>251</td>
</tr>
<tr>
<td>15.1.6</td>
<td>Simplover Model of Bessho Actuator</td>
<td>252</td>
</tr>
<tr>
<td>15.2</td>
<td>VHDL-AMS/Simplover Models</td>
<td>254</td>
</tr>
<tr>
<td>15.2.1</td>
<td>VHDL-AMS Standard IEEE Language</td>
<td>254</td>
</tr>
<tr>
<td>15.2.2</td>
<td>Model of Solenoid Actuator</td>
<td>254</td>
</tr>
<tr>
<td>15.3</td>
<td>MATLAB/Simulink Models</td>
<td>258</td>
</tr>
<tr>
<td>15.3.1</td>
<td>Software</td>
<td>258</td>
</tr>
<tr>
<td>15.3.2</td>
<td>MATLAB Model of Voice Coil Actuator</td>
<td>259</td>
</tr>
<tr>
<td>15.4</td>
<td>Including Eddy Current Diffusion Using a Resistor</td>
<td>264</td>
</tr>
<tr>
<td>15.4.1</td>
<td>Resistor for Planar Devices</td>
<td>264</td>
</tr>
<tr>
<td>15.4.2</td>
<td>Resistor for Axisymmetric Devices</td>
<td>265</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>268</td>
</tr>
<tr>
<td>16.1</td>
<td>Comparing Hydraulics and Magnetics</td>
<td>271</td>
</tr>
<tr>
<td>16.2</td>
<td>Hydraulic Basics and Electrical Analogies</td>
<td>272</td>
</tr>
</tbody>
</table>