

# Contents

## Part I Fundamentals

<b>1</b>	<b>Basic Forms of Model Representation</b> . . . . .	3
1.1	Objectives . . . . .	3
1.2	The General Modelling Approach. . . . .	5
1.3	Physical Modelling, Analogies, and Bond Graphs. . . . .	6
1.4	Block Diagrams . . . . .	10
1.5	Symbolic Model Solving. . . . .	11
1.6	The Object-Oriented Approach. . . . .	12
1.7	Computer Aided Modelling . . . . .	15
1.8	The Book Summary . . . . .	19
	References . . . . .	21
<b>2</b>	<b>Bond Graph Modelling Overview</b> . . . . .	23
2.1	Introduction . . . . .	23
2.2	Word Models. . . . .	23
2.3	Ports, Bonds, and Power Variables . . . . .	24
2.4	Component Model Development . . . . .	26
2.5	Modelling Basic Physical Processes . . . . .	28
2.5.1	Elementary Components . . . . .	28
2.5.2	The Inertial Components . . . . .	29
2.5.3	The Capacitive Components. . . . .	30
2.5.4	The Resistive Components. . . . .	31
2.5.5	The Sources . . . . .	32
2.5.6	The Transformers and Gytrators. . . . .	33
2.5.7	The Effort and Flow Junctions . . . . .	34
2.5.8	Controlled Components . . . . .	35
2.6	Block Diagram Components . . . . .	37
2.6.1	Introduction . . . . .	37
2.6.2	Continuous-Time Components . . . . .	38
2.6.3	Discrete-Time Components . . . . .	40

2.7	Modelling Simple Engineering Systems. . . . .	43
2.7.1	Simple Body Spring Damper System. . . . .	43
2.7.2	The Simple Electrical Circuit . . . . .	48
2.7.3	A See-Saw Problem . . . . .	53
2.8	Causality of Bond Graphs . . . . .	63
2.8.1	The Concept of Causality. . . . .	63
2.8.2	Causalities of Elementary Components . . . . .	64
2.8.3	The Procedure for Assigning Causality . . . . .	67
2.9	The Formulation of the System Equations . . . . .	69
2.10	The Causality Conflicts and Their Resolution. . . . .	72
	References . . . . .	75
<b>3</b>	<b>An Object-Oriented Approach to Modelling . . . . .</b>	<b>77</b>
3.1	Introduction . . . . .	77
3.2	The Component Model . . . . .	77
3.2.1	The Component Class . . . . .	78
3.2.2	The Document Class . . . . .	79
3.3	The Component Class Hierarchy . . . . .	83
3.4	Port and Bond Classes . . . . .	85
3.5	Description of the Element Constitutive Relations. . . . .	89
3.6	Modelling Vector and Higher-Dimensional Quantities . . . . .	90
3.7	Port Connection Rules. . . . .	92
3.8	The Component Set Classes. . . . .	95
3.9	Systematic Top/Down Model Development . . . . .	97
3.10	Component Libraries and Model Reuse . . . . .	100
	References . . . . .	102
<b>4</b>	<b>Object Oriented Modelling in a Visual Environment . . . . .</b>	<b>105</b>
4.1	Introduction . . . . .	105
4.2	The Visual Environment . . . . .	106
4.3	The Component Hierarchy. . . . .	110
4.4	The Port and Bond Classes Hierarchy . . . . .	112
4.5	The Document Architecture . . . . .	112
4.6	Editing Models. . . . .	118
4.6.1	The Editing Box . . . . .	118
4.6.2	Developing Bond Graph Models. . . . .	121
4.6.3	Developing Block Diagram Models. . . . .	126
4.6.4	Modelling Discrete-Time Processes . . . . .	129
4.7	Generating Electrical and Mechanical Schemas. . . . .	131
4.7.1	Developing Electrical Circuits . . . . .	131
4.7.2	Developing Mechanical Circuits . . . . .	134
4.8	Editing Elementary Components Constitutive Relations. . . . .	135
4.8.1	Component Port Dialogues. . . . .	135
4.8.2	Defining the Parameters. . . . .	138

- 4.9 Library Operations . . . . . 141
  - 4.9.1 Library Projects . . . . . 142
  - 4.9.2 Library Components . . . . . 143
- 4.10 Important Operations at the Document Level . . . . . 146
  - 4.10.1 Open, Close and Save Commands. . . . . 147
  - 4.10.2 Page Layout and Print Commands . . . . . 148
  - 4.10.3 The Delete, Copy, Cut, and Insert Operations. . . . . 149
- 4.11 Inter-process Communications . . . . . 151
- References . . . . . 155
- 5 Generation of the Model Equations and Their Solution . . . . . 157**
  - 5.1 Introduction . . . . . 157
  - 5.2 General Forms of the Model Equations . . . . . 158
    - 5.2.1 Generating the System Variables. . . . . 158
    - 5.2.2 Generation of the Equations . . . . . 162
    - 5.2.3 The Characteristics of the Model . . . . . 166
  - 5.3 Numerical Solution Using BDF Methods. . . . . 173
    - 5.3.1 The Implementation of the BDF Method . . . . . 173
    - 5.3.2 The Generation of the Partial Derivative Matrix . . . . . 177
    - 5.3.3 The Error Control Strategy. . . . . 177
  - 5.4 Decompiling the Model Equations . . . . . 180
  - 5.5 The Problem of Starting Values . . . . . 182
  - 5.6 The Treatment of Discontinuities . . . . . 185
  - 5.7 A Stack Based Approach to Function Evaluation . . . . . 186
  - References . . . . . 189

**Part II Applications**

- 6 Mechanical Systems . . . . . 193**
  - 6.1 Introduction . . . . . 193
  - 6.2 The Body Spring Damper Problem. . . . . 194
    - 6.2.1 The Problem . . . . . 194
    - 6.2.2 The Bond Graph Model. . . . . 194
    - 6.2.3 Analysis of the System Behaviour by Simulation . . . . . 208
  - 6.3 Effect of Dry Friction . . . . . 222
    - 6.3.1 The Model of Dry Friction. . . . . 222
    - 6.3.2 Free Vibration of a Body with Dry Friction . . . . . 229
    - 6.3.3 Stick-Slip Motion . . . . . 231
    - 6.3.4 The Stick-Slip Oscillator . . . . . 234
  - 6.4 Bouncing Ball Problems . . . . . 237
    - 6.4.1 Simple Model of Impact . . . . . 237
    - 6.4.2 A Ball Bouncing on a Table. . . . . 241
    - 6.4.3 A Ball Bouncing on a Vibrating Table . . . . . 243
  - 6.5 The Pendulum Problem. . . . . 245
  - References . . . . . 251

- 7 Electrical Systems . . . . . 253**
  - 7.1 Introduction . . . . . 253
  - 7.2 Electrical Circuits . . . . . 254
    - 7.2.1 The Problem . . . . . 254
    - 7.2.2 The Bond Graph Model. . . . . 255
    - 7.2.3 Analysis of the System Behaviour by Simulation . . . 263
  - 7.3 Models of Circuit Elements . . . . . 266
    - 7.3.1 Resistors . . . . . 266
    - 7.3.2 Capacitor . . . . . 267
    - 7.3.3 Inductors . . . . . 269
    - 7.3.4 Sources . . . . . 272
    - 7.3.5 Switches . . . . . 279
  - 7.4 Modelling Semiconductor Components . . . . . 282
    - 7.4.1 Diodes. . . . . 283
    - 7.4.2 Transistors . . . . . 298
    - 7.4.3 Operational Amplifiers. . . . . 317
  - 7.5 Electromagnetic Systems . . . . . 324
    - 7.5.1 Electromagnetic Actuator Problem . . . . . 324
    - 7.5.2 System Bond Graph Model . . . . . 325
    - 7.5.3 Electromagnetic Flux and Force Expressions . . . . . 326
    - 7.5.4 Magnetic Actuator Component Model . . . . . 328
    - 7.5.5 Simulation of Magnetic Actuator Behaviour . . . . . 330
  - References . . . . . 332
- 8 Control Systems . . . . . 333**
  - 8.1 Introduction . . . . . 333
  - 8.2 A Simple Control System . . . . . 334
  - 8.3 PID Control System Modelling . . . . . 343
  - 8.4 Permanent Magnet DC Servo System . . . . . 347
  - References . . . . . 355
- 9 Multibody Dynamics . . . . . 357**
  - 9.1 Introduction . . . . . 357
  - 9.2 Modelling of Rigid Multibody Systems in Plane. . . . . 358
    - 9.2.1 The Component Model of a Rigid Body  
in Planar Motion. . . . . 358
    - 9.2.2 Joints . . . . . 363
    - 9.2.3 Modelling and Simulation of a Planar  
Mechanism . . . . . 368
  - 9.3 Andrews’ Squeezer Mechanism . . . . . 373
  - 9.4 Engine Torsional Vibrations. . . . . 383
  - 9.5 Motion of Constrained Rigid Bodies in Space . . . . . 391
    - 9.5.1 Basic Kinematics . . . . . 391
    - 9.5.2 Bond Graph Representation of a Body Moving  
in Space . . . . . 396

- 9.5.3 Rigid Body Dynamics . . . . . 401
- 9.5.4 Modelling of Body Interconnections in Space. . . . . 404
- 9.6 Dynamics of Puma 560 Robot . . . . . 413
  - 9.6.1 Problem Formulation. . . . . 413
  - 9.6.2 Model of the Robot. . . . . 419
  - 9.6.3 Simulation of PUMA 560 . . . . . 428
- 9.7 3D Visualization of Robots . . . . . 434
  - 9.7.1 Concept of 3D Visualization . . . . . 434
  - 9.7.2 Generating 3D Virtual Scene . . . . . 436
  - 9.7.3 Visualization of Robot Dynamics . . . . . 445
- References . . . . . 447
- 10 Continuous Systems . . . . . 449**
  - 10.1 Introduction . . . . . 449
  - 10.2 Spatial Discretisation of Continuous Systems . . . . . 450
  - 10.3 Model of Electric Transmission Line. . . . . 452
  - 10.4 Bond Graph Model of a Beam . . . . . 459
  - 10.5 A Packaging System Analysis . . . . . 465
    - 10.5.1 Description of the Problem. . . . . 465
    - 10.5.2 Bond Graph Model Development . . . . . 466
    - 10.5.3 Evaluation of Vibration Test Characteristics . . . . . 474
  - 10.6 Coriolis Mass Flowmeters . . . . . 477
    - 10.6.1 Problem Statement . . . . . 477
    - 10.6.2 Principle of Operations . . . . . 478
    - 10.6.3 Dynamics of Curved CMF Tubes . . . . . 480
    - 10.6.4 Bond Graph Model of CMF Transducer . . . . . 490
    - 10.6.5 Control of CMF Transducer . . . . . 494
    - 10.6.6 Simulation of CMF Control Loop . . . . . 501
  - References . . . . . 503
- Appendix . . . . . 505**
- Index . . . . . 507**



<http://www.springer.com/978-3-662-49002-0>

**Mechatronics by Bond Graphs**  
An Object-Oriented Approach to Modelling and  
Simulation

Damić, V.; Montgomery, J.  
2015, XIX, 510 p. 439 illus. in color. With online  
files/update., Hardcover  
ISBN: 978-3-662-49002-0