Contents

Preface vii

Chapter 1
Motion 1

1.1 Introduction 1
1.2 Equilibrium 2
1.3 Dynamics 4
1.4 Modeling 9
1.5 Sports Techniques 12
1.6 Prosthesis 17
1.7 Continuum Approach 18
References 28

Chapter 2
Segmental Movement and Vibrations 29

2.1 Introduction 29
2.2 Examples of Simple Vibration Systems 30
2.3 Strain Energy and the Properties of the Influence Coefficients 32
2.4 Generalized Coordinates 35
2.5 Lagrange's Equations 38
2.6 Normal Modes of Vibration 44
2.7 Decoupling of Equations of Motion 47
2.8 Muscle Forces 49
2.9 Segmental Movement and Vibrations 52
2.10 Systems with Damping and Fluid Dynamic Loads 52
2.11 Sufficient Conditions for Decoupling Equations of System with Damping 55
References 59

Chapter 3
External Flow: Fluid Dynamic Forces Acting on Moving Bodies 62

3.1 Introduction 62
3.2 Flow Around an Airfoil 62
3.3 Flow Around Bluff Bodies 68
3.4 Steady-State Aeroelastic Problems 71
3.5 Transient Fluid Dynamic Forces Due to Unsteady Motion 76
3.6 Flutter 80
3.7 Kutta–Joukowski Theorem 83
3.8 The Creation of Circulation Around a Wing 87
3.9 Circulation and Vorticity in the Wake 88
3.10 Vortex System Associated with a Finite Wing in Nonstationary Motion 91
3.11 Thin Wing in Steady Flow 96
3.12 Lift Distribution on a Finite Wing 99
3.13 Drag 100
References 104

Chapter 4
Flying and Swimming 106

4.1 Introduction 106
4.2 The Conquest of the Air 106
4.3 Comparing Birds and Insects with Aircraft 109
4.4 Forward Flight of Birds and Insects 113
4.5 Hovering and Other Modes of Motion 121
4.6 Aquatic Animal Propulsion 124
4.7 Stokeslet and Dipole in a Viscous Fluid 128
4.8 Motion of Sphere, Cylinder, and Flagella in Viscous Fluid 132
4.9 Resistive-Force Theory of Flagellar Propulsion 135
4.10 Theories of Fish Swimming 140
4.11 Energy Cost of Locomotion 143
4.12 Cell Movement 148
References 150

Chapter 5
Blood Flow in Heart, Lung, Arteries, and Veins 155

5.1 Introduction 155
5.2 The Geometry of the Circulation System 156
5.3 The Materials of the Circulation System 158
5.4 Field Equations and Boundary Conditions 159
5.5 Blood Flow in Heart and Through Heart Valves 161
5.6 Coupling of Left Ventricle to Aorta and Right Ventricle to Pulmonary Artery 162
5.7 Pulsatile Flow in Arteries 165
5.8 Progressive Waves Superposed on a Steady Flow 167
5.9 Reflection and Transmission of Waves at Junctions 168
5.10 Velocity Profile of a Steady Flow in a Tube 170
5.11 Steady Laminar Flow in an Elastic Tube 172
5.12 Velocity Profile of Pulsatile Flow 176
5.13 The Reynolds Number, Stokes Number, and Womersley Number 179
5.14 Equation of Balance of Energy and Work 181

5.15 Systemic Blood Pressure 183
5.16 The Veins and Their Collapsibility 185
5.17 Flow in Collapsible Tubes 190
5.18 Pulse Wave as Message Carrier for Noninvasive Diagnosis 192
References 194

Chapter 6
Micro- and Macrocirculation 196

6.1 Introduction 196
6.2 Anatomy of Microvascular Beds 197
6.3 Major Features of Microcirculation 199
6.4 The Rheological Properties of Blood 202
6.5 General Equations Describing Flow in Microvessels 203
6.6 An Example of Analysis: Pulmonary Blood Flow 203
6.7 Pulmonary Capillary Blood Flow 211
6.8 Waterfall Phenomenon in Zone 2 215
6.9 Open and Closed Capillary Sheets in Zone 2 216
6.10 Synthesis of Micro- and Macrocirculation in the Lung 220
6.11 Validation of the Flow Model 221
References 224

Chapter 7
Respiratory Gas Flow 226

7.1 Introduction 226
7.2 Gas Flow in the Airway 229
7.3 Interaction Between Convection and Diffusion 237
7.4 Exchange Between Alveolar Gas and Erythrocytes 244
7.5 Ventilation—Perfusion Ratio 249
7.6 Pulmonary Function Tests 253
7.7 Dynamics of the Ventilation System 258
7.8 High-Frequency Low-Tidal-Volume Ventilation 265
References 272

Chapter 8
Basic Transport Equations According to Thermodynamics, Molecular Diffusion, Mechanisms in Membranes, and Multiphasic Structure 275

8.1 Introduction 275
8.2 The Laws of Thermodynamics 277
8.3 The Gibbs and Gibbs–Duhem Equations 280
8.4 Chemical Potential 281
8.5 Entropy in a System with Heat and Mass Transfer 283
8.6 Diffusion, Filtration, and Fluid Movement in the Interstitial Space from the Point of View of Thermodynamics 287
8.7 Diffusion from the Molecular Point of View 292
8.8 Transport Across Cell Membranes 294
8.9 Solid Immobile Matrix 300
References 306

Chapter 9
Mass Transport in Capillaries, Tissues, Interstitial Space, Lymphatics, Indicator Dilution Method, and Peristalsis 309

9.1 Introduction 309
9.2 Fluid Movement Across Capillary Blood Vessel Wall 309
9.3 Experimental Determination of the Permeability Characteristics of Capillary Blood Vessel Wall 313
9.4 The Krogh Cylinder as a Model of Oxygen Diffusion from Capillary Blood Vessel to Tissue 316
9.5 Fluid Movement in the Interstitial Space 320
9.6 Measurement of Interstitial Pressure 323
9.7 Pressure in an Incompressible Material 325
9.8 Lymph Flow 330
9.9 Measurement of Extravascular Space by Indicator Dilution Method 333
9.10 Tracer Motion in a Model of Pulmonary Microcirculation 337
9.11 Peristalsis 342
References 348

Chapter 10
Description of Internal Deformation and Forces 353

10.1 Introduction 353
10.2 Description of Internal Deformation 354
10.3 Use of Curvilinear Coordinates 360
10.4 Description of Internal Forces 361
10.5 Equation of Motion in Lagrangian Description 369
10.6 Work and Strain Energy 371
10.7 Calculation of Stresses from the Strain Energy Function 374
10.8 Complementary Energy Function 376
10.9 Rotation and Strain 377
References 381

Chapter 11
Stress, Strain, and Stability of Organs 382

11.1 Introduction 382
11.2 The Zero-Stress State 384
11.3 Stress and Strain in Blood Vessels 388
11.4 Stress and Strain in the Heart 394
11.5 The Musculoskeletal System 400
11.6 The Lung 400
11.7 Surface Tension at the Interface of the Alveolar Gas and Interalveolar Septa 418
11.8 Small Perturbations Superposed on Large Deformation 425
11.9 Derivation of Constitutive Equation on the Basis of Microstructure: Connection Between Micro and Macro Mechanics 431
11.10 Interdependence of Mechanical Properties of Neighboring Organs 438
11.11 Instability of Structures 439
11.12 Collapsed Structure. Example of Atelectatic Lung 443
References 447

Chapter 12
Strength, Trauma, and Tolerance 452

12.1 Introduction 452
12.2 Failure Modes of Materials 453
12.3 Injury and Repair of Organs 460
12.4 Shock Loading and Structural Response 460
12.5 Vibration and the Amplification Spectrum of Dynamic Structural Response 463
12.6 Impact and Elastic Waves 468
12.7 Wave Focusing and Stress Concentration 473
12.8 Trauma of the Lung Due to Impact Load 475
12.9 Cause of Pulmonary Edema in Trauma 478
12.10 Tolerance of Organs to Impact Loads 482
12.11 Biomechanical Modeling 490
12.12 Engineering for Trauma Prevention 491
References 493

Chapter 13
Biomechanical Aspects of Growth and Tissue Engineering 499

13.1 Introduction 499
13.2 Wolff's Law and Roux's Functional Adaptation Concept 500
13.3 Healing of Bone Fracture 503
13.4 Mathematical Formulations of Wolff's Law 508
13.5 Remodeling of Soft Tissues in Response to Stress Changes 511
13.6 Stress Field Created by Fibroblast Cells and Collagen Synthesis 521
13.7 Growth Factors 524
13.8 Significance of Zero-Stress State: Changes Reveal Nonuniform Remodeling 527
13.9 A Hypothesis on Growth 529
13.10 Engineering of Blood Vessels 533
13.11 Tissue Engineering of Skin 534
References 539

Author Index 547

Subject Index 559