Exercises xi
Preface xiii

1. Tire Characteristics and Vehicle Handling and Stability

1.1. Introduction 2
1.2. Tire and Axle Characteristics 3
1.2.1. Introduction to Tire Characteristics 3
1.2.2. Effective Axle Cornering Characteristics 7
1.3. Vehicle Handling and Stability 16
1.3.1. Differential Equations for Plane Vehicle Motions 17
1.3.2. Linear Analysis of the Two-Degree-of-Freedom Model 22
1.3.3. Nonlinear Steady-State Cornering Solutions 35
1.3.4. The Vehicle at Braking or Driving 49
1.3.5. The Moment Method 51
1.3.6. The Car-Trailer Combination 53
1.3.7. Vehicle Dynamics at More Complex Tire Slip Conditions 57

2. Basic Tire Modeling Considerations

2.1. Introduction 59
2.2. Definition of Tire Input Quantities 61
2.3. Assessment of Tire Input Motion Components 68
2.4. Fundamental Differential Equations for a Rolling and Slipping Body 72
2.5. Tire Models (Introductory Discussion) 81

3. Theory of Steady-State Slip Force and Moment Generation

3.1. Introduction 87
3.2. Tire Brush Model 90
3.2.1. Pure Side Slip 92
3.2.2. Pure Longitudinal Slip 97
3.2.3. Interaction between Lateral and Longitudinal Slip (Combined Slip) 100
3.2.4. Camber and Turning (Spin) 112

3.3. The Tread Simulation Model 128
3.4. Application: Vehicle Stability at Braking up to Wheel Lock 140

4. Semi-Empirical Tire Models

4.1. Introduction 150
4.2. The Similarity Method 150
4.2.1. Pure Slip Conditions 152
4.2.2. Combined Slip Conditions 158
4.2.3. Combined Slip Conditions with F_x as Input Variable 163
4.3. The *Magic Formula* Tire Model 165
4.3.1. Model Description 165
4.3.2. Full Set of Equations 176
4.3.3. Extension of the Model for Turn Slip 183
4.3.4. Ply-Steer and Conicity 191
4.3.5. The Overturning Couple 196
4.3.6. Comparison with Experimental Data for a Car, a Truck, and a Motorcycle Tire 202

5. Non-Steady-State Out-of-Plane String-Based Tire Models

5.1. Introduction 212
5.2. Review of Earlier Research 212
5.3. The Stretched String Model 215
5.3.1. Model Development 216
5.3.2. Step and Steady-State Response of the String Model 225
5.3.3. Frequency Response Functions of the String Model 232
5.4. Approximations and Other Models 240
5.4.1. Approximate Models 241
5.4.2. Other Models 256
5.4.3. Enhanced String Model with Tread Elements 258
5.5. Tire Inertia Effects 268
5.5.1. First Approximation of Dynamic Influence (Gyroscopic Couple) 269
5.5.2. Second Approximation of Dynamic Influence (First Harmonic) 271
5.6. Side Force Response to Time-Varying Load 277
5.6.1. String Model with Tread Elements Subjected to Load Variations 277
5.6.2. Adapted Bare String Model 281
5.6.3. The Force and Moment Response 284

6. Theory of the Wheel Shimmy Phenomenon

6.1. Introduction 287
6.2. The Simple Trailing Wheel System with Yaw Degree of Freedom 288

6.3. Systems with Yaw and Lateral Degrees of Freedom 295
6.3.1. Yaw and Lateral Degrees of Freedom with Rigid Wheel/Tire (Third Order) 296
6.3.2. The Fifth-Order System 297
6.4. Shimmy and Energy Flow 311
6.4.1. Unstable Modes and the Energy Circle 311
6.4.2. Transformation of Forward Motion Energy into Shimmy Energy 317
6.5. Nonlinear Shimmy Oscillations 320

7. Single-Contact-Point Transient Tire Models

7.1. Introduction 329
7.2. Model Development 330
7.2.1. Linear Model 330
7.2.2. Semi-Non-Linear Model 335
7.2.3. Fully Nonlinear Model 336
7.2.4. Nonlagging Part 345
7.2.5. The Gyroscopic Couple 348
7.3. Enhanced Nonlinear Transient Tire Model 349

8. Applications of Transient Tire Models

8.1. Vehicle Response to Steer Angle Variations 356
8.2. Cornering on Undulated Roads 356
8.3. Longitudinal Force Response to Tire Nonuniformity, Axle Motions, and Road Unevenness 366
8.3.1. Effective Rolling Radius Variations at Free Rolling 367
8.3.2. Computation of the Horizontal Longitudinal Force Response 371
8.3.3. Frequency Response to Vertical Axle Motions 374
8.3.4. Frequency Response to Radial Run-out 376
8.4. Forced Steering Vibrations 379
8.4.1. Dynamics of the Unloaded System Excited by Wheel Unbalance 380
8.4.2. Dynamics of the Loaded System with Tire Properties Included 382
8.5. ABS Braking on Undulated Road 385
8.5.1. In-Plane Model of Suspension and Wheel/Tire Assembly 386
8.5.2. Antilock Braking Algorithm and Simulation 390
8.6. Starting from Standstill 394

9. Short Wavelength Intermediate Frequency Tire Model

9.1. Introduction 404

9.2. The Contact Patch Slip Model 406
9.2.1. Brush Model Non-Steady-State Behavior 406
9.2.2. The Model Adapted to the Use of the *Magic Formula* 426
9.2.3. Parking Maneuvers 436
9.3. Tire Dynamics 444
9.3.1. Dynamic Equations 444
9.3.2. Constitutive Relations 453
9.4. Dynamic Tire Model Performance 462
9.4.1. Dedicated Dynamic Test Facilities 463
9.4.2. Dynamic Tire Simulation and Experimental Results 466

10. Dynamic Tire Response to Short Road Unevennesses

10.1. Model Development 475
10.1.1. Tire Envelopment Properties 476
10.1.2. The Effective Road Plane Using Basic Functions 478
10.1.3. The Effective Road Plane Using the 'Cam' Road Feeler Concept 485
10.1.4. The Effective Rolling Radius When Rolling Over a Cleat 487
10.1.5. The Location of the Effective Road Plane 493
10.2. *SWIFT* on Road Unevennesses (Simulation and Experiment) 497
10.2.1. Two-Dimensional Unevennesses 497
10.2.2. Three-Dimensional Unevennesses 504

11. Motorcycle Dynamics

11.1. Introduction 506
11.2. Model Description 508
11.2.1. Geometry and Inertia 509
11.2.2. The Steer, Camber, and Slip Angles 511
11.2.3. Air Drag, Driving or Braking, and Fore-and-Aft Load Transfer 514
11.2.4. Tire Force and Moment Response 515
11.3. Linear Equations of Motion 520
11.3.1. The Kinetic Energy 521
11.3.2. The Potential Energy and the Dissipation Function 523
11.3.3. The Virtual Work 524
11.3.4. Complete Set of Linear Differential Equations 525
11.4. Stability Analysis and Step Responses 529
11.4.1. Free Uncontrolled Motion 529
11.4.2. Step Responses of Controlled Motion 536
11.5. Analysis of Steady-State Cornering 539
11.5.1. Linear Steady-State Theory 540
11.5.2. Non-Linear Analysis of Steady-State Cornering 555
11.5.3. Modes of Vibration at Large Lateral Accelerations 563
11.6. The Magic Formula Tire Model 565

12. Tire Steady-State and Dynamic Test Facilities 567

13. Outlines of Three Advanced Dynamic Tire Models

Introduction 577
13.1. The *RMOD-K* Tire Model (Christian Oertel) 578
13.1.1. The Nonlinear FEM Model 578
13.1.2. The Flexible Belt Model 579
13.1.3. Comparison of Various *RMOD-K* Models 581
13.2. The *FTire* Tire Model (Michael Gipser) 582
13.2.1. Introduction 582
13.2.2. Structure Model 583
13.2.3. Tread Model 584
13.2.4. Model Data and Parametrization 586
13.3. The MF-Swift Tire Model (Igo Besselink) 586
13.3.1. Introduction 586
13.3.2. Model Overview 587
13.3.3. MF-Tire/MF-Swift 588
13.3.4. Parameter Identification 589
13.3.5. Test and Model Comparison 589

References 593
List of Symbols 603
Appendix 1. Sign Conventions for Force and Moment and Wheel Slip 609
Appendix 2. Online Information 611
Appendix 3. MF-Tire/MF-Swift Parameters and Estimation Methods 613
Index 627