Contents

Chapter 1 Introduction 1

1.0 Cam-Follower Systems 1
1.1 Fundamentals 1
1.2 Terminology 4
Type of Follower Motion 4
Type of Joint Closure 4
Type of Follower 5
Type of Cam 6
Type of Motion Constraints 8
Type of Motion Program 8
1.3 Applications 9
1.4 Timing Diagrams 11
1.5 Cam Design Software 12
1.6 Units 12
1.7 References 14

Chapter 2 Unacceptable Cam Curves 16

2.0 Introduction 16
2.1 *S V A J* Diagrams 16
2.2 Double-Dwell Cam Design—Choosing S V A J Functions 18
2.3 The Fundamental Law of Cam Design 21
2.4 Simple Harmonic Motion (SHM) 21
2.5 Constant Acceleration (Parabolic Displacement) 24
2.6 Cubic Displacement 24
2.7 Summary 25
2.8 References 25

Chapter 3 Double-Dwell Cam Curves 26

3.0 Introduction 26
3.1 Cycloidal Displacement for Double dwells 26
3.2 Combined Functions for Double dwells 29
Fall Functions 40
3.3 The SCCA Family of Double-Dwell Functions 40
3.4 Polynomial Functions 44
The 3-4-5 Polynomial 45
The 4-5-6-7 Polynomial 48
3.5 Fourier Series Functions 51
3.6 Summary 55
3.7 References 55

Chapter 4 Single-Dwell Cam Curves 56

4.0 Introduction 56
4.1 Single-Dwell Cam Design—Choosing *S V A J* Functions 56
4.2 Single-Dwell Applications of Polynomials 60
Effect of Asymmetry on the Rise-Fall Polynomial Solution 61
4.3 Summary 67

Chapter 5 Spline Functions 68

5.0 Introduction 68
5.1 Classical Splines 69
Knots 69
Interpolation Equations 70
Smoothness Equations 70
Boundary Conditions 71
Computation 73
5.2 General Polynomial Splines 81
5.3 B-splines 85
5.4 Bezier Curves 96
5.5 Shape Preserving Splines 97
Hermite Splines 98
Shumaker Quadratic Splines 100
5.6 Knot Placement 105
5.7 Periodic Splines 114
5.8 Splines Other Than Polynomial Splines 118
Trigonometric Splines 118
Rational Splines 119
5.9 Summary 120
5.10 Bibliography 121

Chapter 6 Critical Path Motion Cam Curves 124

6.0 Introduction 124
6.1 Constant Velocity Motion 124
Polynomials Used for Critical Path Motion 125
Half-Period Harmonic Family Functions 132
6.2 Combined Displacement and Velocity Constraints 136
6.3 Summary 147

Chapter 7 Cam Size Determination 148

7.0 Introduction 148
7.1 Pressure Angle—Radial cam with Translating Roller Follower 149
Eccentricity 150
Choosing a Prime Circle Radius 153
7.2 Pressure Angle—Barrel Cam With Translating Roller Follower 154
7.3 Pressure Angle—Barrel Cam With Oscillating Roller Follower 156
7.4 Overturning Moment—Radial Cam With Translating Flat-Faced Follower 158
7.5 Pressure Angle—Radial Cam With Oscillating Roller Follower 159
7.6 Pressure Angle—Globoidal Cam With Oscillating Roller Follower 162
7.7 Radius of Curvature—Radial Cam With Translating Roller Follower 163
7.8 Radius of Curvature—Radial Cam With Translating Flat-Faced Follower 167
7.9 Radius of Curvature—Barrel Cam With Translating Roller Follower 171
7.10 Radius of Curvature—Barrel Cam With Oscillating Roller Follower 171
7.11 Radius of Curvature—Radial Cam With Oscillating Roller Follower 172
7.12 Radius of Curvature—Radial Cam With Oscillating Flat-Faced Follower 172
Undercutting of Radial Cams with Oscillating Flat-Faced Followers 173
7.13 Radius of Curvature—Globoidal Cam With Oscillating Roller Follower 174
7.14 References 175

Chapter 8 Dynamics of Cam Systems—Modeling Fundamentals 176

8.0 Introduction 176
8.1 Newton's Laws of Motion 176
8.2 Dynamic Models 177
8.3 Mass 177
8.4 Mass Moment and Center of Gravity 178
8.5 Mass Moment of Inertia (Second Moment of Mass) 180
8.6 Parallel Axis Theorem (Transfer Theorem) 181
8.7 Radius of Gyration 182
8.8 Modeling Rotating Links 183
8.9 Lumped Parameter Dynamic Models 184
Spring Rate 184
Damping 184
8.10 Equivalent Systems 187
Combining Dampers 189
Combining Springs 190
Combining Masses 191
Lever and Gear Ratios 191
8.11 Modeling Nonlinear Springs 196
Determining the Effective Spring Rate of an Air Cylinder 200
8.12 Modeling an Industrial Cam-Follower System 205
8.13 References 211

Chapter 9 Dynamics of Cam Systems—Force, Torque, Vibration 212

9.0 Introduction 212
9.1 Dynamic Force Analysis of the Force-Closed Cam-follower 212
Undamped Response 214
Damped Response 216
9.2 Resonance 222
Follower Rise Time 223
9.3 Estimating Damping 225
Logarithmic Decrement 226
9.4 Kinetostatic Force Analysis of the Force-closed Cam-Follower 231
9.5 Kinetostatic Force Analysis of the Form-Closed Cam-Follower 235
9.6 Kinetostatic Camshaft Torque 239
9.7 Controlling Cam Speed—Motors 243
Electric Motors 243
9.8 Controlling Cam Speed—Flywheels 250
9.9 Torque Compensation Cams 256
9.10 References 262

Chapter 10 Modeling Cam-Follower Systems 263

10.0 Introduction 263
10.1 Degrees of Freedom 264
10.2 Single-Mass SDOF Linear Dynamic Models 265
Force-Closed Models 266
Form-Closed Model 268
10.3 Two-Mass, one- or two-DOF, Nonlinear Dynamic Model of a Valve Train 269
10.4 Multi-DOF Dynamic Model of a Valve Train 271
10.5 One-mass Model of an Industrial Cam-Follower System 273
10.6 Two-Mass Model of an Industrial Cam-Follower System 278
10.7 Multi-Degree-of-Freedom (MDOF) Models 281
Two-Degree-of-Freedom Models 281
Three-Degree-of-Freedom Models 285

10.8 Solving 1-DOF System Differential Equations 286
Block Diagram Solution—Simulink/MatLab 286
Ordinary Differential Equation Solution—Using Mathcad 289
State Space Solutions 289
10.9 Solving Multi-DOF System Differential Equation Sets 294
10.10 Modeling a Cam-Follower System With Impact 300
10.11 Polydyne Cam Functions 305
Double-Dwell Polydyne Curves 314
10.12 Splinedyne Cam Functions 323
10.13 References 328

Chapter 11 Residual Vibrations in Cam-Follower Systems 330

11.0 Introduction 330
11.1 Residual Vibration 330
11.2 Residual Vibration of Double-Dwell Functions 331
11.3 Double-Dwell Functions for Low Residual Vibration 334
Freudenstein 1-3 Fourier Series (Harmonic) Function 336
Gutman F-3 Fourier Series (Harmonic) Function 336
Berzak-Freudenstein Polynomials 337
Residual Vibration Spectra for "Low Vibration" Functions 340
Actual Cam Performance Compared to Theoretical Performance 346
11.4 References 348

Chapter 12 Failure of Cam Systems—Stress, Wear, Corrosion 350

12.0 Introduction 350
12.1 Surface Geometry 352
12.2 Mating Surfaces 353
12.3 Adhesive Wear 355
12.4 Abrasive Wear 357
Abrasion-Resistant Materials 357
12.5 Corrosion Wear 357
Corrosion Fatigue 358
Fretting Corrosion 359
12.6 Stress 360
12.7 Strain 362
12.8 Principal Stresses 362
12.9 Plane Stress and Plane Strain 365
Plane Stress 365
Plane Strain 365
12.10 Applied Versus Principal Stresses 366
12.11 Surface Fatigue 367
12.12 Spherical Contact 369
Contact Pressure and Contact Patch in Spherical Contact 369
Static Stress Distributions in Spherical Contact 371
12.13 Cylindrical Contact 373
Contact Pressure and Contact Patch in Parallel Cylindrical Contact 374
Static Stress Distributions in Parallel Cylindrical Contact 375
12.14 General Contact 377
Contact Pressure and Contact Patch in General Contact 378
Stress Distributions in General Contact 379
12.15 Dynamic Contact Stresses 382
Effect of a Sliding Component on Contact Stresses 382
12.16 Surface Fatigue Failure Models—Dynamic Contact 390
12.17 Surface Fatigue Strength 393

12.18 Roller Followers 398
Types of Rolling-Element Bearings 401
12.19 Failure of Rolling-element bearings 401
12.20 Selection of Rolling-Element Bearings 402
Basic Dynamic Load Rating C 402
Basic Static Load Rating C_0 403
Calculation Procedures 403
12.21 References 405

Chapter 13 Cam Profile Determination 407

13.0 Introduction 407
Inversion 408
Digitization Increment 408
13.1 Radial Cams With Roller Followers 409
Offset Translating Roller Follower 409
Oscillating Roller Follower 413
13.2 Radial Cams With Flat-Faced Followers 416
Radial Cams with Translating Flat-Faced Followers 417
Radial Cams with Oscillating Flat-Faced Followers 419
13.3 Barrel Cams With Roller Followers 421
Barrel Cam With Translating Roller Follower 421
Barrel Cam With Oscillating Roller Follower 423
13.4 Linear Cams With Roller Followers 426
13.5 Globoidal Cams with Oscillating Arm Roller Followers 427
13.6 Conjugate Cams 429
Designing Conjugate Cams 429
Conjugate Radial Cams With Translating Followers 429
Conjugate Radial Cams With Oscillating Followers 431
Conjugate Axial Ribbed Cams With Oscillating Followers 432
Indexing Cams 433
13.7 Cam-Linkage Combinations 436
Modifying the Cam Contour for Follower Linkage Geometry 436
13.8 Shifting the Cam Contour to Machine Zero 437
13.9 References 438

Chapter 14 Cam Materials and Manufacturing 439

14.0 Introduction 439
14.1 Cam Materials 440
Cast Irons 440
Wrought Steels 441
Forged Steel 441
Sintered Metals 442
Steel Numbering Systems 442
14.2 Hardness 444
14.3 Heat Treatment 445
Surface (Case) Hardening 447
14.4 Cam Manufacturing Methods 448
Geometric Generation 448
Manual or NC Machining to Cam Coordinates (Plunge-Cutting) 449
Continuous Numerical Control with Linear Interpolation 450
Continuous Numerical Control with Circular Interpolation 453
Analog Duplication 454
14.5 Cutting the Cam 456
Interpolation Method 458
Digitization Increment 458
Resampling the Data 459

Pythagorean Hodographs *460*
14.6 Manufacturing Methods 463
Finishing Processes *463*
Polishing Processes *464*
14.7 Surface Coatings 464
14.8 Measuring the Cam 465
14.9 References 465
14.10 Bibliography 466

Chapter 15 Lubrication of Cam Systems 467

15.0 Introduction 467
15.1 Lubricants 469
15.2 Viscosity 470
15.3 Types of Lubrication 471
Full-Film Lubrication *472*
Boundary Lubrication *475*
15.4 Material Combinations in Cam-Follower Joints 476
15.5 Hydrodynamic Lubrication Theory 476
Petroff's Equation for No-Load Torque *476*
Reynolds' Equation for Eccentric Journal Bearings *477*
15.6 Nonconforming Contacts 480
15.7 Cam Lubrication 487
15.8 References 489

Chapter 16 Cam- and Servo-Driven Mechanisms 490

16.0 Introduction 490
16.1 Servomotors 491
16.2 Servo Motion control 492
Servo Motion Functions 492
16.3 Cam-Driven Linkages 493
16.4 Servo-Driven Linkages 501
16.5 Other Linkages 507
16.6 Cam-Driven Versus Servo-Driven Mechanisms 507
Flexibility *508*
Cost *508*
Reliability *508*
Complexity *508*
Robustness *509*
Packaging *509*
Load Capacity *509*
16.7 References 510
16.8 Bibliography 510

Chapter 17 Measuring Cam-Follower Performance 511

17.0 Introduction 511
17.1 Transducers 511
Angular Position Transducers *512*
Displacement Transducers *513*
Velocity Transducers *515*
Strain Transducers *515*
Force Transducers *515*
Acceleration Transducers *517*
Vibration Measurement *518*

17.2 Experimental Cam-Follower Measurements 519
17.3 Data Analysis 520
Analog to Digital Conversion 520
Spectrum Analysis 522
Forms of Spectra 525
Modal Domain 526
Frequency Response Functions (FRF) 527
Dynamic Signal Analyzers 528
Measuring the FRF 528
The "Q" of a System 530
Convolution and Deconvolution 531
17.4 References 534
17.5 Bibliography 534

Chapter 18 Case Studies 535

18.0 Introduction 535
18.1 Analyzing Vibrations in an IC Engine Valve Train 535
Conclusions 546
18.2 Analyzing Vibrations in Cam-Driven Automated Assembly Machinery 547
Conclusions 555
18.3 References 556

Chapter 19 Cam Design Guidelines 557

19.0 Introduction 557
19.1 Practical Design Considerations 557
Translating or Oscillating Follower? 557
Force or Form-Closed? 558
Radial or Barrel Cam? 559
Roller or Flat-Faced Follower? 559
To Dwell or Not to Dwell? 561
To Grind or Not to Grind? 561
To Lubricate or Not to Lubricate? 562
What Double-Dwell Cam Program to Use? 563
What Cam Program to Use For Difficult or Complicated Motions? 563
To Polydyne or Not to Polydyne? 563
Camshaft Design 564
Follower Train Design 564
Follower Train Dynamics 564
Natural Frequencies 565
Backlash 565
How Important is Theoretical Peak Acceleration? 565
19.2 Rules of Thumb for Cam Design 566
19.3 References 568

Appendix A Computer Programs 569

Appendix B Material Properties 571

Appendix C Geometric Properties 575

Bibliography 577

Glossary of Terms 597

Index 599