

Contents

Chapter 1 Introduction	1
1.0 Cam-Follower Systems	1
1.1 Fundamentals	1
1.2 Terminology	4
<i>Type of Follower Motion</i>	4
<i>Type of Joint Closure</i>	4
<i>Type of Follower</i>	5
<i>Type of Cam</i>	6
<i>Type of Motion Constraints</i>	8
<i>Type of Motion Program</i>	8
1.3 Applications	9
1.4 Timing Diagrams	10
1.5 Cam Design Software	10
1.6 Units	10
1.7 References	16
Chapter 2 Unacceptable Cam Curves	17
2.0 Introduction	17
2.1 S V A J Diagrams	17
2.2 Double-Dwell Cam Design—Choosing S V A J Functions	19
2.3 The Fundamental Law of Cam Design	22
2.4 Simple Harmonic Motion (SHM)	22
2.5 Constant Acceleration (Parabolic Displacement)	25
2.6 Cubic Displacement	25
2.7 Summary	26
2.8 References	26
Chapter 3 Double-Dwell Cam Curves	27
3.0 Introduction	27
3.1 Cycloidal Displacement for Double Dwells	27
3.2 Combined Functions for Double Dwells	30
<i>Fall Functions</i>	41
3.3 The SCCA Family of Double-Dwell Functions	41
3.4 Polynomial Functions	45
<i>The 3-4-5 Polynomial</i>	46
<i>The 4-5-6-7 Polynomial</i>	49
3.5 Fourier Series Functions	52
3.6 Summary	56
3.7 References	56
Chapter 4 Single-Dwell Cam Curves	57
4.0 Introduction	57
4.1 Single-Dwell Cam Design—Choosing S V A J Functions	57
4.2 Single-Dwell Applications of Polynomials	61
<i>Effect of Asymmetry on the Rise-Fall Polynomial Solution</i>	63
4.3 Summary	68

Chapter 5 Spline Functions 69

5.0 Introduction 69

5.1 Classical Splines 70

Knots 70

Smoothness Equations 71

Interpolation Equations 72

Boundary Conditions 72

5.2 General Polynomial Splines 81

5.3 B-splines 86

5.4 Bezier Curves 97

5.5 Knot Placement 105

5.6 Periodic Splines 115

5.7 Splines Other Than Polynomial Splines 119

Trigonometric Splines 119

Rational Splines 122

5.8 Summary 123

5.9 Bibliography 124

Chapter 6 Critical Path Motion (CPM) Cam Curves 127

6.0 Introduction 127

6.1 Constant Velocity Motion 127

Polynomials Used for Critical Path Motion 128

Half-Period Harmonic Family Functions 135

6.2 Combined Displacement and Velocity Constraints 139

6.3 Summary 150

Chapter 7 Cam Size Determination 151

7.0 Introduction 151

7.1 Pressure Angle—Radial Cam with Translating Roller Follower 152

Eccentricity 153

Choosing a Prime Circle Radius 156

7.2 Pressure Angle—Barrel Cam With Translating Roller Follower 157

7.3 Pressure Angle—Barrel Cam With Oscillating Roller Follower 159

7.4 Overturning Moment—Radial Cam With Translating Flat-Faced Follower 161

7.5 Pressure Angle—Radial Cam With Oscillating Roller Follower 162

7.6 Radius of Curvature—Radial Cam With Translating Roller Follower 165

7.7 Radius of Curvature—Radial Cam With Translating Flat-Faced Follower 169

7.8 Radius of Curvature—Barrel Cam With Translating Roller Follower 173

7.9 Radius of Curvature—Barrel Cam With Oscillating Roller Follower 173

7.10 Radius of Curvature—Radial Cam With Oscillating Roller Follower 174

7.11 Radius of Curvature—Radial Cam With Oscillating Flat-Faced Follower 174

Undercutting of Radial Cams with Oscillating Flat-Faced Followers 175

7.12 References 176

Chapter 8 Dynamics of Cam Systems—Modeling Fundamentals 177

8.0 Introduction 177

8.1 Newton’s Laws of Motion 177

8.2 Dynamic Models 178

8.3 Mass 178

8.4 Mass Moment and Center of Gravity 179

8.5 Mass Moment of Inertia (Second Moment of Mass) 181

8.6 Parallel Axis Theorem (Transfer Theorem) 182

8.7 Radius of Gyration 183

8.8 Modeling Rotating Links 184

8.9 Lumped Parameter Dynamic Models 185

Spring Rate 185

Damping 185

8.10	Equivalent Systems	188
	<i>Combining Dampers</i>	190
	<i>Combining Springs</i>	191
	<i>Combining Masses</i>	192
	<i>Lever and Gear Ratios</i>	192
8.11	Modeling Nonlinear Springs	197
	<i>Determining the Effective Spring Rate of an Air Cylinder</i>	201
8.12	Modeling an Industrial Cam-Follower System	206
8.13	References	212
Chapter 9 Dynamics of Cam Systems—Force, Torque, Vibration		213
9.0	Introduction	213
9.1	Dynamic Force Analysis of the Force-Closed Cam-Follower	213
	<i>Undamped Response</i>	215
	<i>Damped Response</i>	217
9.2	Resonance	224
	<i>Follower Rise Time</i>	226
9.3	Estimating Damping	227
	<i>Logarithmic Decrement</i>	227
9.4	Kinetostatic Force Analysis of the Force-Closed Cam-Follower	233
9.5	Kinetostatic Force Analysis of the Form-Closed Cam-Follower	238
9.6	Kinetostatic Camshaft Torque	241
9.7	Controlling Cam Speed—Motors	246
	<i>Electric Motors</i>	246
9.8	Controlling Cam Speed—Flywheels	251
9.9	Torque Compensation Cams	258
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
	<i>Force-Closed Models</i>	266
	<i>Form-Closed Model</i>	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	272
10.5	One-Mass Model of an Industrial Cam-Follower System	273
10.6	Two-Mass Model of an Industrial Cam-Follower System	279
10.7	Solving System Differential Equations	282
	<i>Block Diagram Solution—Simulink/MatLab</i>	282
	<i>Ordinary Differential Equation Solution—Using Mathcad</i>	284
	<i>State Space Solutions</i>	286
10.8	Polydyne Cam Functions	291
	<i>Double-Dwell Polydyne Curves</i>	299
10.9	Splinedyne Cam Functions	307
10.10	References	312
Chapter 11 Residual Vibrations in Cam-Follower Systems		315
11.0	Introduction	315
11.1	Residual Vibration	315
11.2	Residual Vibration of Double-Dwell Functions	316
11.3	Double-Dwell Functions for Low Residual Vibration	319
	<i>Freudenstein 1-3 Fourier Series (Harmonic) Function</i>	321
	<i>Gutman F-3 Fourier Series (Harmonic) Function</i>	321
	<i>Berzak-Freudenstein Polynomials</i>	322
	<i>Residual Vibration Spectra for "Low Vibration" Functions</i>	325
	<i>Actual Cam Performance Compared to Theoretical Performance</i>	331
11.4	References	333

Chapter 12 Failure of Cam Systems—Stress, Wear, Corrosion 335

12.0	Introduction	335
12.1	Surface Geometry	337
12.2	Mating Surfaces	338
12.3	Adhesive Wear	340
12.4	Abrasive Wear	342
	<i>Abrasion-Resistant Materials</i>	342
12.5	Corrosion Wear	342
	<i>Corrosion Fatigue</i>	343
	<i>Fretting Corrosion</i>	344
12.6	Stress	345
12.7	Strain	347
12.8	Principal Stresses	347
12.9	Plane Stress and Plane Strain	350
	<i>Plane Stress</i>	350
	<i>Plane Strain</i>	350
	Applied Versus Principal Stresses	351
12.11	Surface Fatigue	352
12.12	Spherical Contact	354
	<i>Contact Pressure and Contact Patch in Spherical Contact</i>	355
	<i>Static Stress Distributions in Spherical Contact</i>	356
12.13	Cylindrical Contact	358
	<i>Contact Pressure and Contact Patch in Parallel Cylindrical Contact</i>	359
	<i>Static Stress Distributions in Parallel Cylindrical Contact</i>	360
12.14	General Contact	363
	<i>Contact Pressure and Contact Patch in General Contact</i>	363
	<i>Stress Distributions in General Contact</i>	364
12.15	Dynamic Contact Stresses	368
	<i>Effect of a Sliding Component on Contact Stresses</i>	368
12.16	Surface Fatigue Failure Models—Dynamic Contact	376
12.17	Surface Fatigue Strength	379
12.18	Roller Followers	386
	<i>Types of Rolling-Element Bearings</i>	387
12.19	Failure of Rolling-Element bearings	387
12.20	Selection of Rolling-Element Bearings	388
	<i>Basic Dynamic Load Rating C</i>	388
	<i>Basic Static Load Rating C₀</i>	390
	<i>Calculation Procedures</i>	390
12.21	References	391

Chapter 13 Cam Profile Determination 393

13.0	Introduction	393
	<i>Inversion</i>	394
	<i>Digitization Increment</i>	394
13.1	Radial Cams With Roller Followers	395
	<i>Offset Translating Roller Follower</i>	395
	<i>Oscillating Roller Follower</i>	399
13.2	Radial Cams With Flat-Faced Followers	402
	<i>Radial Cams with Translating Flat-Faced Followers</i>	403
	<i>Radial Cams with Oscillating Flat-Faced Followers</i>	405
13.3	Barrel Cams With Roller Followers	407
	<i>Barrel Cam With Translating Roller Follower</i>	407
	<i>Barrel Cam With Oscillating Roller Follower</i>	409
13.4	Linear Cams With Roller Followers	412
13.5	Conjugate Cams	413
	<i>Designing Conjugate Cams</i>	415
	<i>Conjugate Radial Cams With Translating Followers</i>	415
	<i>Conjugate Radial Cams With Oscillating Followers</i>	416
	<i>Conjugate Axial Ribbed Cams With Oscillating Followers</i>	417
	<i>Indexing Cams</i>	418
13.6	Cam-Linkage Combinations	419
	<i>Modifying the Cam Contour for Follower Linkage Geometry</i>	421

13.7	Shifting the Cam Contour to Machine Zero	421
13.8	References	422
Chapter 14 Cam Materials and Manufacturing		423
14.0	Introduction	423
14.1	Cam Materials	424
	<i>Cast Irons</i>	424
	<i>Wrought Steels</i>	425
	<i>Forged Steel</i>	425
	<i>Sintered Metals</i>	426
	<i>Steel Numbering Systems</i>	426
14.2	Hardness	428
14.3	Heat Treatment	429
	<i>Surface (Case) Hardening</i>	431
14.4	Cam Manufacturing Methods	432
	<i>Geometric Generation</i>	432
	<i>Manual or NC Machining to Cam Coordinates (Plunge-Cutting)</i>	433
	<i>Continuous Numerical Control with Linear Interpolation</i>	434
	<i>Continuous Numerical Control with Circular Interpolation</i>	437
	<i>Analog Duplication</i>	438
14.5	Cutting the Cam	440
	<i>Interpolation Method</i>	442
	<i>Digitization Increment</i>	442
	<i>Resampling the Data</i>	443
	<i>Pythagorean Hodographs</i>	444
14.6	Manufacturing Methods	447
	<i>Finishing Processes</i>	447
	<i>Polishing Processes</i>	448
14.7	Surface Coatings	448
14.8	Measuring the Cam	449
14.9	References	449
14.10	Bibliography	450
Chapter 15 Lubrication of Cam Systems		451
15.0	Introduction	451
15.1	Lubricants	453
15.2	Viscosity	454
15.3	Types of Lubrication	455
	<i>Full-Film Lubrication</i>	457
	<i>Boundary Lubrication</i>	460
15.4	Material Combinations in Cam-Follower Joints	460
15.5	Hydrodynamic Lubrication Theory	461
	<i>Petroff's Equation for No-Load Torque</i>	461
	<i>Reynolds' Equation for Eccentric Journal Bearings</i>	462
15.6	Nonconforming Contacts	465
15.7	Cam Lubrication	472
15.8	References	473
Chapter 16 Measuring Cam-Follower Performance		475
16.0	Introduction	475
16.1	Transducers	475
	<i>Angular Position Transducers</i>	476
	<i>Displacement Transducers</i>	477
	<i>Velocity Transducers</i>	479
	<i>Strain Transducers</i>	479
	<i>Force Transducers</i>	479
	<i>Acceleration Transducers</i>	481
	<i>Vibration Measurement</i>	482
16.2	Experimental Cam-Follower Measurements	483
16.3	Data Analysis	484

	Analog to Digital Conversion	484
	Spectrum Analysis	486
	Forms of Spectra	489
	Modal Domain	491
	Frequency Response Functions (FRF)	491
	Dynamic Signal Analyzers	492
	Measuring the FRF	492
	The "Q" of a System	494
	Convolution and Deconvolution	495
16.4	References	498
16.5	Bibliography	498
Chapter 17 Case Studies		499
17.0	Introduction	499
17.1	Analyzing Vibrations in an IC Engine Valve Train	499
	Conclusions	510
17.2	Analyzing Vibrations in Cam-Driven Automated Assembly Machinery	511
	Conclusions	519
17.3	References	520
Chapter 18 Cam Design Guidelines		521
18.0	Introduction	521
18.1	Practical Design Considerations	521
	Translating or Oscillating Follower?	521
	Force or Form-Closed?	522
	Radial or Barrel Cam?	523
	Roller or Flat-Faced Follower?	523
	To Dwell or Not to Dwell?	525
	To Grind or Not to Grind?	525
	To Lubricate or Not to Lubricate?	526
	What Double-Dwell Cam Program to Use?	527
	What Cam Program to Use For Difficult or Complicated Motions?	527
	To Polydyne or Not to Polydyne?	527
	Camshaft Design	528
	Follower Train Design	528
	Follower Train Dynamics	528
	Natural Frequencies	529
	Backlash	529
	How Important is Theoretical Peak Acceleration?	529
18.2	Rules of Thumb for Cam Design	530
18.3	References	532
Appendix A Computer Programs		533
A.0	Introduction	533
A.1	General information	533
	Hardware Requirements	533
	Operating System Requirements	533
	Demonstration Versions	533
	Installing the Software	534
	How to Use This Manual	534
A.2	General Program Operation	534
	Running the Programs (All Programs)	534
	The Home Screen (All Programs)	534
	General User Actions Possible Within a Program (All Programs)	535
	Units (All Programs)	535
	Examples (All Programs)	535
	Creating New, Saving, and Opening Files (File - All Programs)	535
	Copying Screens to Clipboard or Printer (Copy - All Programs)	536
	Printing to Screen, Printer, and Exporting Disk Files (Print Button)	536
	Plotting Data (Plot Button)	537
	The About Menu (All Programs)	541

	<i>Exiting a Program (All Programs)</i>	541
	<i>Support (All Programs)</i>	541
A.3	Program DYNACAM	541
	<i>The DYNACAM Home Screen</i>	541
	<i>Input Data (DYNACAM Input Screen)</i>	541
	<i>Polynomial Functions</i>	544
	<i>Spline Functions</i>	545
	<i>Back to the Input Screen</i>	546
	<i>Continuity Check Screen</i>	546
	<i>Sizing the Cam</i>	546
	<i>Drawing the Cam</i>	547
	<i>Exporting Cam Contour Data (DYNACAM Only)</i>	549
	<i>Kinetostatic Analysis (DYNACAM Only)</i>	549
	<i>Dynamic Analysis (DYNACAM Only)</i>	550
	<i>Stress Analysis (DYNACAM Only)</i>	552
	<i>Fourier Transform (FFT)</i>	553
	<i>Other</i>	554
A.4	Program FOURBAR	554
	<i>The FOURBAR Home Screen</i>	554
	<i>Input Data (FOURBAR Input Screen)</i>	554
	<i>Calculation (FOURBAR, FIVEBAR, SIXBAR, and SLIDER Input Screens)</i>	555
	<i>Animation (FOURBAR)</i>	557
	<i>Dynamics (FOURBAR, FIVEBAR, SIXBAR, and SLIDER Dynamics Screen)</i>	558
	<i>Balancing (FOURBAR Only)</i>	561
	<i>Cognates (FOURBAR Only)</i>	561
	<i>Synthesis (FOURBAR Only)</i>	562
	<i>Other</i>	562
A.5	Program SIXBAR	562
	<i>The SIXBAR Home Screen</i>	562
	<i>Input Data (SIXBAR Input Screen)</i>	564
	<i>Animation (SIXBAR)</i>	565
	<i>Dynamics (SIXBAR Dynamics Screen)</i>	565
	<i>Other</i>	565
A.6	Program SLIDER	565
	<i>The SLIDER Home Screen</i>	565
	<i>Input Data (SLIDER Input Screen)</i>	565
	<i>Calculation (SLIDER Input Screen)</i>	566
	<i>Animation (SLIDER Animation Screen)</i>	566
	<i>Dynamics (SLIDER Dynamics Screen)</i>	566
	<i>Other</i>	567
	Appendix B Material Properties	569
	Appendix C Geometric Properties	573
	Appendix D Spring Data	575
	Bibliography	579
	Glossary of Terms	599
	Index	601
	Index to CD-ROM	609
	Installation Instructions for CD-ROM	610