

# Contents

<b>Chapter 1 Introduction</b> .....	<b>1</b>
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
<b>Chapter 2 Unacceptable Cam Curves</b> .....	<b>17</b>
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
<b>Chapter 3 Double-Dwell Cam Curves</b> .....	<b>27</b>
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
<b>Chapter 4 Single-Dwell Cam Curves</b> .....	<b>57</b>
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

<b>Chapter 5 Spline Functions .....</b>	<b>69</b>
5.0 Introduction .....	69
5.1 Classical Splines .....	70
<i>Knots</i> .....	70
<i>Interpolation Equations</i> .....	71
<i>Smoothness Equations</i> .....	71
<i>Boundary Conditions</i> .....	72
<i>Computation</i> .....	74
5.2 General Polynomial Splines .....	82
5.3 B-splines .....	86
5.4 Bezier Curves .....	97
5.5 Shape Preserving Splines .....	98
<i>Hermite Splines</i> .....	99
<i>Shumaker Quadratic Splines</i> .....	101
5.6 Knot Placement .....	106
5.7 Periodic Splines .....	115
5.8 Splines Other Than Polynomial Splines .....	119
<i>Trigonometric Splines</i> .....	119
<i>Rational Splines</i> .....	120
5.9 Summary .....	121
5.10 Bibliography .....	122
<b>Chapter 6 Critical Path Motion Cam Curves .....</b>	<b>125</b>
6.0 Introduction .....	125
6.1 Constant Velocity Motion .....	125
<i>Polynomials Used for Critical Path Motion</i> .....	126
<i>Half-Period Harmonic Family Functions</i> .....	133
6.2 Combined Displacement and Velocity Constraints .....	137
6.3 Summary .....	148
<b>Chapter 7 Cam Size Determination .....</b>	<b>149</b>
7.0 Introduction .....	149
7.1 Pressure Angle—Radial cam with Translating Roller Follower .....	150
<i>Eccentricity</i> .....	151
<i>Choosing a Prime Circle Radius</i> .....	154
7.2 Pressure Angle—Barrel Cam With Translating Roller Follower .....	155
7.3 Pressure Angle—Barrel Cam With Oscillating Roller Follower .....	157
7.4 Overturning Moment—Radial Cam With Translating Flat-Faced Follower .....	159
7.5 Pressure Angle—Radial Cam With Oscillating Roller Follower .....	160
7.6 Pressure Angle—Globoidal Cam With Oscillating Roller Follower .....	163
7.7 Radius of Curvature—Radial Cam With Translating Roller Follower .....	164
7.8 Radius of Curvature—Radial Cam With Translating Flat-Faced Follower .....	168
7.9 Radius of Curvature—Barrel Cam With Translating Roller Follower .....	172
7.10 Radius of Curvature—Barrel Cam With Oscillating Roller Follower .....	172
7.11 Radius of Curvature—Radial Cam With Oscillating Roller Follower .....	173
7.12 Radius of Curvature—Radial Cam With Oscillating Flat-Faced Follower .....	173
<i>Undercutting of Radial Cams with Oscillating Flat-Faced Followers</i> .....	174
7.13 Radius of Curvature—Globoidal Cam With Oscillating Roller Follower .....	175
7.14 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
	<i>Spring Rate</i> .....	185
	<i>Damping</i> .....	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 ..... 265**

10.0	Introduction .....	265
10.1	Degrees of Freedom .....	266
10.2	Single-Mass SDOF Linear Dynamic Models .....	267
	<i>Force-Closed Models</i> .....	268
	<i>Form-Closed Model</i> .....	270
10.3	Two-Mass, one- or two-DOF, Nonlinear Dynamic Model of a Valve Train .....	271
10.4	Multi-DOF Dynamic Model of a Valve Train .....	274
10.5	One-mass Model of an Industrial Cam-Follower System .....	275
10.6	Two-Mass Model of an Industrial Cam-Follower System .....	281
10.7	Multi-Degree-of-Freedom (MDOF) Models .....	284
	<i>Two-Degree-of-Freedom Models</i> .....	284
	<i>Three-Degree-of-Freedom Models</i> .....	288

10.8	Solving 1-DOF System Differential Equations .....	289
	<i>Block Diagram Solution—Simulink/MatLab</i> .....	289
	<i>Ordinary Differential Equation Solution—Using Mathcad</i> .....	293
	<i>State Space Solutions</i> .....	294
10.9	Solving Multi-DOF System Differential Equation sets† .....	297
10.10	Modeling a Cam-Follower System With impact .....	305
10.11	Polydyne Cam Functions .....	308
	<i>Double-Dwell Polydyne Curves</i> .....	317
10.12	Splinedyne Cam Functions .....	326
10.13	References .....	331
<b>Chapter 11 Residual Vibrations in Cam-Follower Systems .....</b>		<b>333</b>
11.0	Introduction .....	333
11.1	Residual Vibration .....	333
11.2	Residual Vibration of Double-Dwell Functions .....	334
11.3	Double-Dwell Functions for Low Residual Vibration .....	337
	<i>Freudenstein 1-3 Fourier Series (Harmonic) Function</i> .....	339
	<i>Gutman F-3 Fourier Series (Harmonic) Function</i> .....	339
	<i>Berzak-Freudenstein Polynomials</i> .....	340
	<i>Residual Vibration Spectra for "Low Vibration" Functions</i> .....	343
	<i>Actual Cam Performance Compared to Theoretical Performance</i> .....	349
11.4	References .....	351
<b>Chapter 12 Failure of Cam Systems—Stress, Wear, Corrosion .....</b>		<b>353</b>
12.0	Introduction .....	353
12.1	Surface Geometry .....	355
12.2	Mating Surfaces .....	356
12.3	Adhesive Wear .....	358
12.4	Abrasive Wear .....	360
	<i>Abrasion-Resistant Materials</i> .....	360
12.5	Corrosion Wear .....	360
	<i>Corrosion Fatigue</i> .....	361
	<i>Fretting Corrosion</i> .....	362
12.6	Stress .....	363
12.7	Strain .....	365
12.8	Principal Stresses .....	365
12.9	Plane Stress and Plane Strain .....	368
	<i>Plane Stress</i> .....	368
	<i>Plane Strain</i> .....	368
12.10	Applied Versus Principal Stresses .....	369
12.11	Surface Fatigue .....	370
12.12	Spherical Contact .....	372
	<i>Contact Pressure and Contact Patch in Spherical Contact</i> .....	373
	<i>Static Stress Distributions in Spherical Contact</i> .....	374
12.13	Cylindrical Contact .....	376
	<i>Contact Pressure and Contact Patch in Parallel Cylindrical Contact</i> .....	377
	<i>Static Stress Distributions in Parallel Cylindrical Contact</i> .....	378
12.14	General Contact .....	381
	<i>Contact Pressure and Contact Patch in General Contact</i> .....	381
	<i>Stress Distributions in General Contact</i> .....	382
12.15	Dynamic Contact Stresses .....	386
	<i>Effect of a Sliding Component on Contact Stresses</i> .....	386
12.16	Surface Fatigue Failure Models—Dynamic Contact .....	394
12.17	Surface Fatigue Strength .....	397

12.18	Roller Followers .....	403
	<i>Types of Rolling-Element Bearings</i> .....	404
12.19	Failure of Rolling-element bearings .....	405
12.20	Selection of Rolling-Element Bearings .....	405
	<i>Basic Dynamic Load Rating C</i> .....	406
	<i>Basic Static Load Rating C<sub>0</sub></i> .....	407
	<i>Calculation Procedures</i> .....	407
12.21	References .....	409
<b>Chapter 13 Cam Profile Determination .....</b>		<b>411</b>
13.0	Introduction .....	411
	<i>Inversion</i> .....	412
	<i>Digitization Increment</i> .....	412
13.1	Radial Cams With Roller Followers .....	413
	<i>Offset Translating Roller Follower</i> .....	413
	<i>Oscillating Roller Follower</i> .....	417
13.2	Radial Cams With Flat-Faced Followers .....	420
	<i>Radial Cams with Translating Flat-Faced Followers</i> .....	421
	<i>Radial Cams with Oscillating Flat-Faced Followers</i> .....	423
13.3	Barrel Cams With Roller Followers .....	425
	<i>Barrel Cam With Translating Roller Follower</i> .....	425
	<i>Barrel Cam With Oscillating Roller Follower</i> .....	427
13.4	Linear Cams With Roller Followers .....	430
13.5	Globoidal Cams with Oscillating Arm Roller Followers .....	431
13.6	Conjugate Cams .....	433
	<i>Designing Conjugate Cams</i> .....	433
	<i>Conjugate Radial Cams With Translating Followers</i> .....	433
	<i>Conjugate Radial Cams With Oscillating Followers</i> .....	435
	<i>Conjugate Axial Ribbed Cams With Oscillating Followers</i> .....	436
	<i>Indexing Cams</i> .....	437
13.6	Cam-Linkage Combinations .....	440
	<i>Modifying the Cam Contour for Follower Linkage Geometry</i> .....	440
13.7	Shifting the Cam Contour to Machine Zero .....	441
13.8	References .....	442
<b>Chapter 14 Cam Materials and Manufacturing .....</b>		<b>443</b>
14.0	Introduction .....	443
14.1	Cam Materials .....	444
	<i>Cast Irons</i> .....	444
	<i>Wrought Steels</i> .....	445
	<i>Forged Steel</i> .....	445
	<i>Sintered Metals</i> .....	446
	<i>Steel Numbering Systems</i> .....	446
14.2	Hardness .....	448
14.3	Heat Treatment .....	449
	<i>Surface (Case) Hardening</i> .....	451
14.4	Cam Manufacturing Methods .....	452
	<i>Geometric Generation</i> .....	452
	<i>Manual or NC Machining to Cam Coordinates (Plunge-Cutting)</i> .....	453
	<i>Continuous Numerical Control with Linear Interpolation</i> .....	454
	<i>Continuous Numerical Control with Circular Interpolation</i> .....	457
	<i>Analog Duplication</i> .....	458

14.5	Cutting the Cam .....	460
	<i>Interpolation Method</i> .....	462
	<i>Digitization Increment</i> .....	462
	<i>Resampling the Data</i> .....	463
	<i>Pythagorean Hodographs</i> .....	464
14.6	Manufacturing Methods .....	467
	<i>Finishing Processes</i> .....	467
	<i>Polishing Processes</i> .....	468
14.7	Surface Coatings .....	468
14.8	Measuring the Cam .....	469
14.9	References .....	469
14.10	Bibliography .....	470
<b>Chapter 15 Lubrication of Cam Systems .....</b>		<b>471</b>
15.0	Introduction .....	471
15.1	Lubricants .....	473
15.2	Viscosity .....	474
15.3	Types of Lubrication .....	475
	<i>Full-Film Lubrication</i> .....	477
	<i>Boundary Lubrication</i> .....	480
15.4	Material Combinations in Cam-Follower Joints .....	480
15.5	Hydrodynamic Lubrication Theory .....	481
	<i>Petroff's Equation for No-Load Torque</i> .....	481
	<i>Reynolds' Equation for Eccentric Journal Bearings</i> .....	482
15.6	Nonconforming Contacts .....	485
15.7	Cam Lubrication .....	492
15.8	References .....	493
<b>Chapter 16 Measuring Cam-Follower Performance .....</b>		<b>495</b>
16.0	Introduction .....	495
16.1	Transducers .....	495
	<i>Angular Position Transducers</i> .....	496
	<i>Displacement Transducers</i> .....	497
	<i>Velocity Transducers</i> .....	499
	<i>Strain Transducers</i> .....	499
	<i>Force Transducers</i> .....	499
	<i>Acceleration Transducers</i> .....	501
	<i>Vibration Measurement</i> .....	502
16.2	Experimental Cam-Follower Measurements .....	503
16.3	Data Analysis .....	504
	<i>Analog to Digital Conversion</i> .....	504
	<i>Spectrum Analysis</i> .....	506
	<i>Forms of Spectra</i> .....	509
	<i>Modal Domain</i> .....	510
	<i>Frequency Response Functions (FRF)</i> .....	511
	<i>Dynamic Signal Analyzers</i> .....	512
	<i>Measuring the FRF</i> .....	512
	<i>The "Q" of a System</i> .....	514
	<i>Convolution and Deconvolution</i> .....	515
16.4	References .....	518
16.5	Bibliography .....	518

<b>Chapter 17 Case Studies .....</b>	<b>519</b>
17.0 Introduction .....	519
17.1 Analyzing Vibrations in an IC Engine Valve Train .....	519
<i>Conclusions</i> .....	530
17.2 Analyzing Vibrations in Cam-Driven Automated Assembly Machinery .....	531
<i>Conclusions</i> .....	539
17.3 References .....	540
<b>Chapter 18 Cam Design Guidelines .....</b>	<b>541</b>
18.0 Introduction .....	541
18.1 Practical Design Considerations .....	541
<i>Translating or Oscillating Follower?</i> .....	541
<i>Force or Form-Closed?</i> .....	542
<i>Radial or Barrel Cam?</i> .....	543
<i>Roller or Flat-Faced Follower?</i> .....	543
<i>To Dwell or Not to Dwell?</i> .....	545
<i>To Grind or Not to Grind?</i> .....	545
<i>To Lubricate or Not to Lubricate?</i> .....	546
<i>What Double-Dwell Cam Program to Use?</i> .....	547
<i>What Cam Program to Use For Difficult or Complicated Motions?</i> .....	547
<i>To Polydyne or Not to Polydyne?</i> .....	547
<i>Camshaft Design</i> .....	548
<i>Follower Train Design</i> .....	548
<i>Follower Train Dynamics</i> .....	548
<i>Natural Frequencies</i> .....	549
<i>Backlash</i> .....	549
<i>How Important is Theoretical Peak Acceleration?</i> .....	549
18.2 Rules of Thumb for Cam Design .....	550
18.3 References .....	552
<b>Appendix A Computer Programs .....</b>	<b>553</b>
A.1 Downloadable Programs .....	553
A.2 General information .....	553
<i>Hardware/System Requirements</i> .....	553
<i>Installing the Software</i> .....	553
<i>User Manual</i> .....	554
<i>Example Files</i> .....	554
<b>Appendix B Material Properties .....</b>	<b>555</b>
<b>Appendix C Geometric Properties .....</b>	<b>559</b>
<b>Bibliography .....</b>	<b>561</b>
<b>Glossary of Terms .....</b>	<b>581</b>
<b>Index .....</b>	<b>583</b>