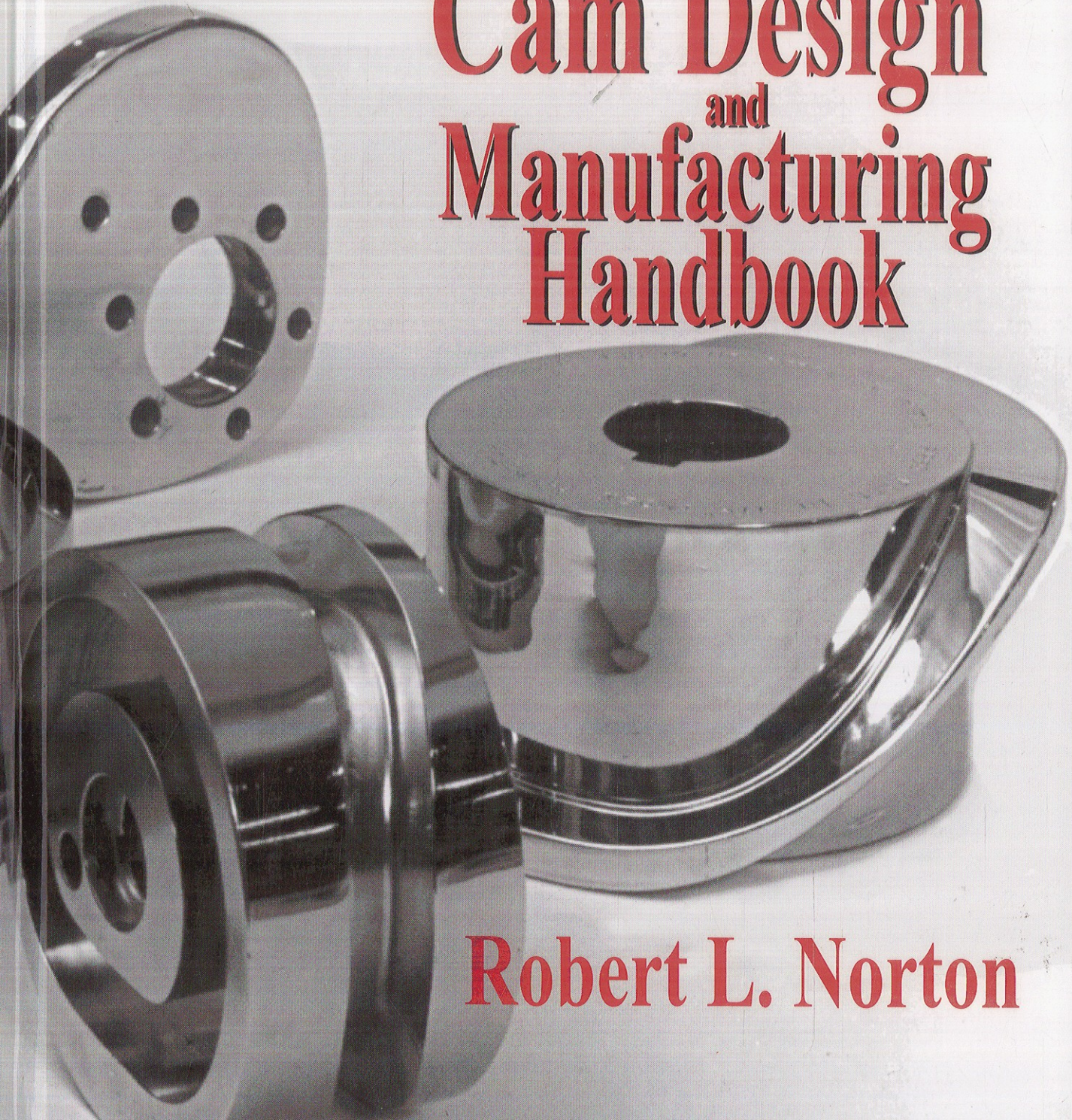


Second Edition

Cam Design and Manufacturing Handbook



Robert L. Norton

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 |
| | <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 |
| | | |
| Chapter 6 | Critical Path Motion Cam Curves | 125 |
| 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 |
| | | |
| Chapter 7 | Cam Size Determination | 149 |
| 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 | Kinestatic Force Analysis of the Force-closed Cam-Follower | 233 |
| 9.5 | Kinestatic Force Analysis of the Form-Closed Cam-Follower | 238 |
| 9.6 | Kinestatic 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 |

Chapter 11 Residual Vibrations in Cam-Follower Systems 333

| | | |
|------|---|-----|
| 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>Gufman 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 |

Chapter 12 Failure of Cam Systems—Stress, Wear, Corrosion 353

| | | |
|-------|---|-----|
| 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 | 362 |
| | <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 C₀</i> | 407 |
| | <i>Calculation Procedures</i> | 407 |
| 12.21 | References | 409 |

Chapter 13 Cam Profile Determination 411

| | | |
|------|--|-----|
| 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 |

Chapter 14 Cam Materials and Manufacturing 443

| | | |
|------|---|-----|
| 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 |
| | Interpolation Method | 462 |
| | Digitization Increment | 462 |
| | Resampling the Data | 463 |
| | Pythagorean Hodographs | 464 |
| 14.6 | Manufacturing Methods | 467 |
| | Finishing Processes | 467 |
| | Polishing Processes | 468 |
| 14.7 | Surface Coatings | 468 |
| 14.8 | Measuring the Cam | 469 |
| 14.9 | References | 469 |
| 14.10 | Bibliography | 470 |

Chapter 15 Lubrication of Cam Systems471

| | | |
|------|---|-----|
| 15.0 | Introduction | 471 |
| 15.1 | Lubricants | 473 |
| 15.2 | Viscosity | 474 |
| 15.3 | Types of Lubrication | 475 |
| | Full-Film Lubrication | 477 |
| | Boundary Lubrication | 480 |
| 15.4 | Material Combinations in Cam-Follower Joints | 480 |
| 15.5 | Hydrodynamic Lubrication Theory | 481 |
| | Petroff's Equation for No-Load Torque | 481 |
| | Reynolds' Equation for Eccentric Journal Bearings | 482 |
| 15.6 | Nonconforming Contacts | 485 |
| 15.7 | Cam Lubrication | 492 |
| 15.8 | References | 493 |

Chapter 16 Measuring Cam-Follower Performance495

| | | |
|------|--|-----|
| 16.0 | Introduction | 495 |
| 16.1 | Transducers | 495 |
| | Angular Position Transducers | 496 |
| | Displacement Transducers | 497 |
| | Velocity Transducers | 499 |
| | Strain Transducers | 499 |
| | Force Transducers | 499 |
| | Acceleration Transducers | 501 |
| | Vibration Measurement | 502 |
| 16.2 | Experimental Cam-Follower Measurements | 503 |
| 16.3 | Data Analysis | 504 |
| | Analog to Digital Conversion | 504 |
| | Spectrum Analysis | 506 |
| | Forms of Spectra | 509 |
| | Modal Domain | 510 |
| | Frequency Response Functions (FRF) | 511 |
| | Dynamic Signal Analyzers | 512 |
| | Measuring the FRF | 512 |
| | The "Q" of a System | 514 |
| | Convolution and Deconvolution | 515 |
| 16.4 | References | 518 |
| 16.5 | Bibliography | 518 |

| | |
|--|------------|
| Chapter 17 Case Studies | 519 |
| 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 |
| | |
| Chapter 18 Cam Design Guidelines | 541 |
| 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>Rackial 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 |
| | |
| Appendix A Computer Programs | 553 |
| 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 |
| | |
| Appendix B Material Properties | 555 |
| | |
| Appendix C Geometric Properties | 559 |
| | |
| Bibliography | 561 |
| | |
| Glossary of Terms | 581 |
| | |
| Index | 583 |