Contents

Chapter 1 Introduction 1

1.1 Mechanical Design 1
1.2 Optimum Design 2
1.3 Some Aspects of a Specific Design Problem 3
The Basic Design Problem 3
Adequate Design Solution 3
Optimum Design Solution 4
Some Salient Characteristics of the Preceding Design Studies 11

Evolution of the Method of Optimum Design—Some Industrial Examples 11

1.4 Optimum Design by Necessity 11
1.5 High Speed Geneva Mechanism 12
1.6 An Unconventional High Speed Intermittent Motion Mechanism 15
1.7 Optimum Design of a High Speed Cam Mechanism 19
1.8 Optimal Design for Practical Mechanical Elements 20
References 21

Chapter 2 Some Mathematical Background 22

Some Approximations for Practical Functions 22

2.1 Simplicity and Accuracy Considerations 22
2.2 Mathematical Functions in Engineering 24

2.3	Conversion Processes for Function Expression	25
2.4	Errors in Conversion Processes	26
2.5	Review of Continuous and Differentiable Functions	26
2.6	Approximating Derivatives by Finite Differences	28
2.7	Some Examples of Methods for Regenerative Conversions—Curve Fitting	35
	Function Conversion to a Polynomial Series	36
	Example 2.1	38
	Function Conversion to a Simple Exponential Equation	39
	Example 2.2	42
	Function Conversion to Simple Exponential Equation Referred to Shifted Coordinate Axes	43
	Example 2.3	49
	Function Conversion by Graphical Iteration	54
	Function Conversion by Least Squares Regression Analysis	55
	Example 2.4	56
	Function Conversion for Cases of Many Variables	57
2.8	Some Examples of Methods for Degenerative Conversions—Simplification	59
	Neglect of Terms in Finite Series	60
	Example 2.5	60
	Consideration of Finite Number of Terms in Convergent Infinite Series	62
	Example 2.6	62
	Example 2.7	64
	Simplification of Complex Equations by Curve Fitting on Tabulated or Graphical Data	65
	Estimating the Effects of Relative Changes in Independent Variables for Simple Exponential Equations	67
	Some Basic Search Techniques for Automated Optimal Design	69
2.9	Single Variable Search for the Extreme	69
	Example 2.8	72
2.10	Multivariable Search for the Extreme	73
	Direction of Steepest Descent	75
	Search for the Extreme along a Ray	78

Example 2.9 79
Example 2.10 82
Multivariables Search Summary 83
References 85
Exercises 85

Chapter 3 Manufacturing Errors and Product Performance 88

3.1 Significant Types of Manufacturing Errors 88
3.2 Some Relationships of Stress and Acceleration to Curvature 90
3.3 Effects of Minute Displacement Errors on Curvature and on Rigid Accelerations or Theoretical Stresses 96
Example 3.1 98
Example 3.2 99
Example 3.3 102
Example 3.4 103
3.4 Effects of Minute Displacement Errors on Actual Product Performance and Product Life 105
Example 3.5 106
Surface Finish Effects 108
Contacting Surface Flaws 110
Minute Imperfections on Constraining Elements for Bodies in Motion 111
3.5 Conclusions 113
References 114
Exercises 114

Chapter 4 Material Properties and Failure Theories 116

4.1 Stress and Strength 116
Material Properties 117
4.2 Some Material Properties Related to Strength 117
Fatigue Strength of Steel 118
4.3 Some Material Properties Other than Strengths 118
Review of Combined Stress Systems 121
4.4 Unique Definition and Distribution of Stress Systems 121

4.5 Principal Stresses 122
Significant Theories of Failure 126
4.6 Purpose and Choice of the Failure Criterion for Design 126
4.7 Static Stress Criteria for Failure 128
Maximum Normal Stress Theory 128
Maximum Shearing Stress Theory 129
Distortion Energy Theory 129
Comparison of Significant Theories with Experimental Evidence 129
4.8 Varying Stress Criteria for Failure 131
Maximum Shearing Stress Theory of Fatigue Failure 132
Von Mises-Hencky Criterion for Fatigue Failure 135
Octahedral Shear Stress Criterion for Triaxial State Fatigue Failure 135
Example 4.1 136
4.9 Surface Wear Criteria for Failure 136
Abrasive Wear 137
Adhesive Wear 137
Example 4.2 138
Surface Fatigue 139
Example 4.3 141
References 141
Exercises 142

Chapter 5 Factor of Safety in Design 145

5.1 Actual Load and Load Capability for a Mechanical Element 146
5.2 Statistical Nature of Actual Load 148
5.3 Statistical Nature of Load Capability 149
5.4 Basic Relationship between Statistical Distributions for Actual Load and Load Capability of a General Mechanical Element 150
5.5 Normal or Gaussian Distribution of a Variable 153
5.6 Relationship of Actual Load λ to Load Capability L, Assuming Normal Distributions 157

Example 5.1 161
Example 5.2 163
5.7 Selection of Factor of Safety Based on Percentage Estimates for Tolerances on Actual Load and Load Capability 165
Example 5.3 166
Example 5.4 167
5.8 Selection of a Factor of Safety for the Case Where the Occurrence of the Failure Phenomenon Would be Disastrous 168
Example 5.5 168
Example 5.6 169
5.9 Resolution of $(\Delta\lambda/\bar{\lambda})$ and $(\Delta L/\bar{L})$ into Components 170
Example 5.7 173
5.10 Conclusions 174
References 175
Exercises 175

Chapter 6 Some Optimization Techniques for Mechanical Elements 178

Some Basic Background for Mechanical Elements 179
6.1 Structures and Machines 179
6.2 General Characteristics of Mechanical Elements 179
6.3 Bases of Mechanical Design 184
6.4 A General Viewpoint on Typical Design Equations 184
6.5 Adequate Design 187
6.6 Optimum Design 187
6.7 Choosing the Basic Geometrical Shape 189
6.8 A General Mathematical Viewpoint on Optimum Design 190
6.9 Primary Design Equation 193
6.10 Subsidiary Design Equations 194
6.11 Constraints 194
6.12 Summary of Design Equations in Optimum Design 195
Method of Optimum Design (MOD) 197
6.13 General Description of MOD 197

	Some Guidelines for Problem Formulation	197
	Basic Procedural Steps for MOD	198
	Types of Variables in (I.F.)	199
	Types of Problems in MOD	200
	General Planning, (I.F.) to (F.F.) in MOD	201
	Some Features of the MOD	203
	Some Limitations of the MOD	204
6.14	Case of Normal Specifications (N.S.) for Mechanical Elements	205
	Example 6.1	207
6.15	Case of Redundant Specifications (R.S.) for Mechanical Elements	211
	Example 6.2	214
	Example 6.3	217
	Example 6.4	221
6.16	Case of Incompatible Specifications (I.S.) for Mechanical Elements	225
	Example 6.5	226
6.17	Modification of Boundary Values	229
6.18	Problems with More than One Primary Design Equation	230
	Automated Optimal Design (AOD)	231
6.19	Basic Equation System Format for AOD	232
	Basic Format for AOD Equation Systems	233
	Example 6.6	234
6.20	Normalized Equation Systems for AOD	235
	Unit Based Variables	235
	Unit Based Equations	236
	Unit Based AOD Equation System Format	237
	Example 6.7	238
6.21	Penalized Optimization Quantity, (QP)	239
6.22	Minima–Maxima Equivalence	240
6.23	Good Start Point Strategy	241
	Random Number Generation	242
	Random Design Point Generation	243
	Good Start Point Choice	244

OPTIGO 245

6.24 OPTIGO General Description 245
6.25 OPTIGO Main Program 247
Initial Calculations 247
Start Point for the Search 250
Stepping Increments Along a Ray from Base Point B_r 250
Converging to Minimum (QP) Along a Ray 251
Distance δ_r between Successive Base Points 252
Convergence to the Solution Point 252
6.26 SUBROUTINE PRTOUT 253
6.27 SUBROUTINE SG 254
6.28 SUBROUTINE QPCALC 255
6.29 SUBROUTINE Q5000 256
Special Functions and Final Items: F_j's 256
6.30 SUBROUTINE EJ6000 257
6.31 SUBROUTINE RK7000 258
6.32 SUBROUTINE INPUT 258
6.33 Size Limitations for OPTIGO 260
6.34 Self-Tuning Probes for C_p 261
6.35 Application of OPTIGO 263
Mode (1): Shotgun Start and Automatic C_p Determinations 264
Mode (2): Specified Start Point and Automatic C_p Determination 264
Mode (3): Specified C_p Value and Start Point 264
Example 6.8 265
Example 6.9 267
6.36 Some Characteristics of OPTIGO in Operation 270
Characteristics of Normal Convergence by OPTIGO 270
Remedial Action for Unusual Cases 271
Example 6.10 271
6.37 Special Refinements in OPTIGO 274
Recommendation for General Application of OPTIGO 275
References 275
Exercises 277

Chapter 7 Optimal Design of Simple Mechanical Elements 280

7.1 Tensile Bar in Dynamic Loading 280
7.2 Torsion in Simple Cylindrical Bars 284
7.3 Simple Torsion Bar for Minimum Weight 286
7.4 Practical Deviations from Simple Geometry 290
7.5 Practical Torsion Bar for Minimum Weight 296
7.6 Torsion Shaft for Minimum Cost 305
7.7 Torsion Shaft for Minimum Dynamic Torque 309
Initial Formulation 310
Exploratory Calculations 312
Final Formulation 312
Variation Study 314
General Guidelines for Flow Chart Synthesis in MOD 317
Example 7.1 319
7.8 Dynamic Shaft in Combined Loading, (N.S.) 322
Statement of the Problem 322
Optimum Design of the Torsion Bar Spring 325
Example 7.2 333
7.9 Dynamic Shaft in Combined Loading, (R.S.) 334
Final Formulation 335
Variation Study 336
Flow Chart Derivation 339
Numerical Application 340
Exercises 341
General Problem Statement 341

Chapter 8 Optimal Design of Complex Mechanical Elements 364

8.1 Optimal Design of Helical and Spur Gears 365
Initial Formulation 366
Exploratory Calculations 380
Approach 1 (F.F.) 382
Strategy for Simplification of the Variation Study 390
Simplified (F.F.), Approach 2 392
Variation Study with P_{nd} and N_p Constant 393
Calculation Flow Chart 395
Example 8.1 398
Common Input Values for Problems A through E 399

8.2 Optimal Design of Helical Springs 401
Basic Background Information 401
Objectives for Optimum Design 408
Boundary Conditions for the Triple Optimization Problem 409
Initial Formulation for Triple Optimization Problem 410
Exploratory Calculations 410
Planning the Attack 412
Final Formulation for Triple Optimization Problem 412
Variation Study for Triple Optimization Problem 414
Flow Chart for Triple Optimization Problem 418
Example 8.2 423
Common Input Data for Five Problems 423
Solutions to Optimization Problems 423
8.3 Optimal Design of Capillary-Compensated Hydrostatic Journal Bearings 424
Some Nomenclature for Bearing Design 425
Objective for Optimal Design 425
Basic Equations for Design Use 427
Criterion Function for AOD 432
Constraints and Specified Items 432
Analysis for a Design State Point 432
Unit Based Variables 433
AOD Equations for Use in OPTIGO 434
Programming of Equations in OPTIGO 435
Example 8.3 441
References 445
Exercises 446
Gearset Design Problems 446
Helical Compression Spring Design Problems 448
Hydrostatic Journal Bearing Design Problems 449
Other Complex Mechanical Element Design Problems 450
Design of a Cylindrical Roller Bearing 450
Hydrodynamic Journal Bearing Design 453

Varying Motion Mechanisms 456
Geneva Mechanism Design 457
Selection of Standard Bearing for Cam Follower 460
Gearbox Design 464
Brake Design 466
Pivoted Shoe Brake Design Problem 468
Pivoted Shoe Brake Design Application 471

Appendix A Some Basic Nomenclature for MOD and AOD 473

A.1 Method of Optimum Design 473
General Notation with MOD 473
Exploratory Calculation Notation for MOD 474
A.2 Automated Optimal Design by OPTIGO 474
Tabulated Descriptions in Text 474
Some Other Items 474

Appendix B Optigo Fortran IV Listing and Sample Printouts 476

B.1 Fortran IV Listing of OPTIGO 477
B.2 Optigo Printout Samples from Example 6.9(b) of Chapter 6 483

Appendix C An Acceptable-Point Algorithm for Design Optimization 488

C.1 Nomenclature 488
C.2 Introduction 489
C.3 Descent Methods for Unconstrained Function Minimization 491
Conjugate Directions 492
C.4 Operations of the GCG–GSAP Algorithm 494
GCG Algorithm 495
GSAP Univariate Algorithm 495
C.5 Optimal Design of a Torsion Bar Spring 496
Index to Computer Program of Figure C.1 503
References 506

Index 509