

Contents

1	Introduction.....	1
1.1	What is Engineering Design?	1
1.2	Role and Classification of Design	4
1.3	Analytic Design Methodology	6
1.4	Axiomatic Design.....	7
1.5	Design Optimization.....	8
1.6	Structural Optimization	9
1.7	Structural Optimization Under Dynamic Loads	11
1.8	Design with DOE	12
1.9	Robust Design	13
1.10	Multidisciplinary Design Optimization	13
1.11	Summary.....	15
2	Axiomatic Design	17
2.1	Introduction	17
2.2	The Independence Axiom.....	19
2.2.1	The Independence Axiom.....	19
2.2.2	Independence	25
2.2.3	Physical Integration	32
2.3	The Information Axiom.....	33
2.3.1	The Calculation of Information Contents Using Probability	33
2.3.2	Probability Density Function and Information Content	35
2.3.3	The Calculation of Information Content for a Decoupled Design	38
2.4	The Application of Axiomatic Design.....	52
2.5	Software Design Using the Axiomatic Approach	64
2.5.1	Software Design	64
2.5.2	Conventional Languages and Axiomatic Design	64
2.5.3	Object Oriented Programming and Axiomatic Design.....	69
2.6	Discussion	71
2.7	Exercises.....	72
2.A	Corollaries and Theorems.....	76
2.B	Axiomatic Design of a Beam Adjuster for a Laser Marker.....	82
2.B.1	Problem Description.....	82

2.B.2	Axiomatic Analysis of an Existing Design.....	84
2.B.3	The Development of a New Beam Adjuster.....	86
2.B.4	Summary.....	89
2.C	The Development of a Design System for a TV Glass Bulb.....	90
2.C.1	Problem Description.....	90
2.C.2	The Conventional Design Process for a Glass Bulb.....	90
2.C.3	Automatic Design Software for Product Design.....	92
2.C.4	Software Development.....	95
2.C.5	Summary.....	97
2.D	The Development of a Design System for the EPS Cushioning Package of a Monitor.....	99
2.D.1	Problem Description.....	99
2.D.2	The Development of an Automatic Design System for the EPS Cushioning Package.....	99
2.D.3	Summary.....	103
3	Design Optimization.....	107
3.1	Introduction.....	107
3.2	Optimization Problems in Engineering.....	109
3.3	Analytic Optimization Methods.....	115
3.3.1	Graphical Optimization.....	116
3.3.2	Unconstrained Optimization.....	116
3.3.3	Constrained Optimization.....	119
3.4	General Concepts of Numerical Methods in Optimization.....	122
3.5	Linear Programming.....	125
3.5.1	Standardization of Linear Programming.....	125
3.5.2	Basic Concepts of Linear Programming.....	129
3.5.3	Terminologies of LP.....	131
3.5.4	Simplex Method.....	131
3.6	One-dimensional Minimization.....	133
3.6.1	Equal Interval Search.....	134
3.6.2	Golden Section Search.....	135
3.7	Numerical Methods for Unconstrained Optimization.....	138
3.7.1	Steepest Descent Method.....	138
3.7.2	Conjugate Gradient Method.....	141
3.7.3	Quasi-Newton Method.....	142
3.8	Numerical Methods for Constrained Optimization.....	144
3.8.1	General Aspects of the Primal Method.....	145
3.8.2	Primal Method.....	149
3.8.3	Transformation Method.....	153
3.9	Exercises.....	154
3.A	Brief Review of Mathematical Terminologies and Background.....	163

4	Structural Optimization	171
4.1	Introduction	171
4.2	Finite Element Method	172
4.2.1	Stress and Strain	173
4.2.2	Formulation of the Finite Element Method	174
4.3	Formulation of Structural Optimization	187
4.4	Sensitivity Analysis	200
4.4.1	Finite Difference Method	200
4.4.2	Analytic Method with Discrete Equations	205
4.4.3	Semianalytic Method	214
4.4.4	Analytic Sensitivity Analysis Using Continuum Equations	216
4.5	Methods of Structural Optimization	221
4.5.1	Direct Method	221
4.5.2	Approximation Method	222
4.5.3	Multiple Loading Conditions and Design Variable Linking	226
4.6	Application of Structural Optimization	229
4.6.1	Size Optimization	229
4.6.2	Shape Optimization	231
4.6.3	Topology Optimization	237
4.7	Exercises	240
4.A	Automotive Door Design with the ULSAB Concept Using Structural Optimization	244
4.A.1	Problem Description	244
4.A.2	The Design Process for Weight Reduction	244
5	Dynamic Response Optimization	255
5.1	Introduction	255
5.2	Optimization in the Time Domain	256
5.3	Time-dependent Constraints	257
5.3.1	Treatment of Time-dependent Constraints in the Direct Method	257
5.3.2	Treatment of Time-dependent Constraints in the Transformation Method	263
5.4	Sensitivity Analysis	265
5.4.1	Direct Differentiation Method	265
5.4.2	Adjoint Variable Method	270
5.4.3	Time Finite Element Method	274
5.5	Approximation	276
5.5.1	Global Approximation	276
5.5.2	Local Approximation	277
5.6	A Method Using Equivalent Static Loads	279
5.6.1	Equivalent Static Loads	279
5.6.2	Optimization in the Time Domain Using Equivalent Static Loads	281
5.6.3	Optimization of Flexible Multibody Dynamic Systems	286

5.7	Structural Optimization in the Frequency Domain.....	292
5.7.1	Optimization of Harmonic Responses	292
5.7.2	Sensitivity Analysis	295
5.7.3	Treatment of Constraints and Minimization of the Maximum Amplitude	301
6	Design of Experiments	309
6.1	Introduction	309
6.2	Design of Experiments (DOE)	311
6.2.1	One-way Factorial Design	312
6.2.2	Two-way Factorial Design	317
6.3	Design Using Orthogonal Arrays	325
6.3.1	Orthogonal Arrays	325
6.3.2	Analysis of Experimental Results Using Orthogonal Arrays ...	327
6.3.3	Design Using Orthogonal Arrays	336
6.4	Design with Orthogonal Arrays Considering Interactions	340
6.5	Design Using Orthogonal Arrays for Constrained Problems	351
6.6	Sequential Algorithm with Orthogonal Arrays (SOA).....	357
6.7	Design Using the Response Surface Method	360
6.7.1	Introduction	360
6.7.2	Generation of the Response Surface.....	362
6.7.3	Optimization Using the Response Surface Method.....	368
6.7.4	Selection of Candidate Points and Analysis of the Optimization Results	371
6.8	Exercises.....	372
6.A	Statistics.....	382
6.B	Orthogonal Arrays.....	386
6.B.1	Orthogonal Arrays with Two Levels.....	386
6.B.2	Orthogonal Arrays with Three Levels	388
6.B.3	Orthogonal Array with Mixed Levels	390
7	Robust Design.....	393
7.1	Introduction	393
7.2	Mean and Variance.....	394
7.3	Taguchi Method	399
7.3.1	Introduction	399
7.3.2	The Loss Function and S/N Ratio.....	401
7.3.3	Parameter Design.....	404
7.3.4	Various Methods Using the Taguchi Method.....	412
7.4	Robust Optimization.....	416
7.4.1	Introduction	416
7.4.2	Robustness of the Objective Function	418
7.4.3	Robustness of Constraints	421
7.4.4	Optimization Methods	425

7.5	Robust Design by Axiomatic Design	428
7.6	The Robustness Index	429
7.7	Summary.....	435
7.8	Exercises.....	435
8	Case Studies with Analytic Design Methods.....	443
8.1	Introduction	443
8.2	Design of a Strip Casting Roll.....	444
8.2.1	Problem Description	444
8.2.2	Optimization Formulation for a Strip Casting Roll	446
8.2.3	Optimization Results	448
8.2.4	Summary.....	454
8.3	Design of a Spacer Grid Spring.....	455
8.3.1	Problem Description	455
8.3.2	Design Requirements.....	456
8.3.3	Optimization of the Grid Spring.....	457
8.3.4	Summary.....	462
8.4	Design of an Automobile Rearview Mirror.....	464
8.4.1	Finite Element Modelling of the Rearview Mirror.....	464
8.4.2	Topology Optimization of the Rearview Mirror.....	467
8.4.3	Size Optimization of the Rearview Mirror	468
8.4.4	Design Using Orthogonal Arrays in a Discrete Space.....	469
8.4.5	Robust Design of the Rearview Mirror	472
8.5	Structural Analysis and Optimization of a Low Speed Vehicle Body ..	474
8.5.1	Problem Description	474
8.5.2	The Aluminum Space Frame and the Low Speed Vehicle	475
8.5.3	Structural Analysis of the Low Speed Vehicle and a Comparative Study with a General Passenger Car	477
8.5.4	Improvement of the Low Speed Vehicle Using Structural Optimization.....	489
8.5.5	Summary.....	494
9	Application of Design Methods to Automobile Safety Problems.....	497
9.1	Introduction	497
9.2	Modelling for Safety Simulation	499
9.2.1	Modelling for Multibody Dynamic Analysis.....	499
9.2.2	Modelling Using Nonlinear Finite Element Analysis.....	501
9.3	Design of an Airbag Using Orthogonal Arrays.....	502
9.4	Design of an Energy Absorbing Steering System Using Orthogonal Arrays	504
9.4.1	Problem Description	504
9.4.2	Modelling of the Energy Absorbing Steering System	505
9.4.3	Validation of the Model Through the Body Block Test	506
9.4.4	Parameter Study of the Energy Absorbing Parts	508

9.4.5	Definition of the Objective Function.....	510
9.4.6	Design Using Orthogonal Arrays	511
9.4.7	Summary.....	513
9.5	Design of a Side Impact Beam of an Automobile Door	513
9.5.1	Problem Description	513
9.5.2	Problem Formulation	515
9.5.3	Design of an Impact Beam Using Orthogonal Arrays.....	516
9.5.4	Design Using the Response Surface Method.....	516
9.5.5	Summary.....	518
9.6	Design of a Motor Driven Tilt/Telescopic Steering System.....	519
9.6.1	Problem Description	519
9.6.2	Conceptual Design Using Axiomatic Design	519
9.6.3	Detailed Design for Safety	521
9.6.4	Detailed Design Considering Vibration.....	526
9.6.5	Summary.....	530
9.7	Crash Analysis and Design of a Belt Integrated Seat for Occupant Safety.....	530
9.7.1	Problem Description	530
9.7.2	Simulation Modelling	532
9.7.3	Simulation of Frontal and Rear Impacts	533
9.7.4	Structural Optimization of the BIS	540
9.7.5	Summary.....	544
9.8	Determination of a Crash Pulse and Optimization of Crash Components Using Response Surface Approximate Optimization	545
9.8.1	Problem Description	545
9.8.2	Response Surface Approximate Optimization.....	545
9.8.3	Determination of a Crash Pulse to Minimize Occupant Injury.....	547
9.8.4	Optimization Formulation for the Determination of a Crash Pulse	548
9.8.5	Frontal Crash with an Airbag	550
9.8.6	Rear End Impact	552
9.8.7	Design of Safety Devices for a Frontal Crash	553
9.8.8	Seat Design in Rear End Impact.....	556
9.8.9	Summary.....	558
10	Multidisciplinary Design Optimization.....	561
10.1	Introduction	561
10.2	Multidisciplinary Design Optimization	563
10.2.1	Coupling in Analysis	564
10.2.2	Formulation of MDO.....	566
10.2.3	Classification of MDO Methods.....	567
10.3	Basic Theories for MDO Methods	571
10.3.1	Linear Decomposition and Global Sensitivity Equation	571
10.3.2	Optimum Sensitivity	575
10.4	Multidisciplinary Design Optimization Methods	579

10.4.1 Multidisciplinary Feasible (MDF).....	579
10.4.2 Individual Discipline Feasible (IDF).....	580
10.4.3 All-at-once (AAO).....	582
10.4.4 Concurrent Subspace Optimization (CSSO)	585
10.4.5 Bilevel Integrated System Synthesis (BLISS).....	593
10.4.6 Collaborative Optimization (CO)	597
10.4.7 Multidisciplinary Design Optimization Based on Independent Subspaces (MDOIS)	602
10.4.8 Comparison of MDO Methods	605
10.5 Discussion	608
10.A Application of an MDO Algorithm to the Design of a Belt Integrated Seat Taking Crashworthiness into Consideration.....	609
10.A.1 Problem Description	609
10.A.2 The Interdisciplinary Relationship Between the Disciplines Involved.....	610
10.A.3 Formulation for the Design of a BIS Taking Crashworthiness into Consideration	610
10.A.4 Application of MDOIS to the Design of a BIS.....	611
Index	621

