Contents

Preface to the Second Edition xvii
Preface to the First Edition xix
Suggestions of Topics for Instructors xxiii
List of Experiments and Data Sets xxv

1 Basic Concepts for Experimental Design and Introductory Regression Analysis 1
   1.1 Introduction and Historical Perspective, 1
   1.2 A Systematic Approach to the Planning and Implementation of Experiments, 4
   1.3 Fundamental Principles: Replication, Randomization, and Blocking, 8
   1.4 Simple Linear Regression, 11
   1.5 Testing of Hypothesis and Interval Estimation, 14
   1.6 Multiple Linear Regression, 20
   1.7 Variable Selection in Regression Analysis, 26
   1.8 Analysis of Air Pollution Data, 29
   1.9 Practical Summary, 34
Exercises, 36
References, 43

2 Experiments with a Single Factor 45
   2.1 One-Way Layout, 45
       *2.1.1 Constraint on the Parameters, 50
CONTENTS

2.2 Multiple Comparisons, 53
2.3 Quantitative Factors and Orthogonal Polynomials, 57
2.4 Expected Mean Squares and Sample Size Determination, 63
2.5 One-Way Random Effects Model, 70
2.6 Residual Analysis: Assessment of Model Assumptions, 74
2.7 Practical Summary, 79
Exercises, 80
References, 86

3 Experiments with More Than One Factor 87
3.1 Paired Comparison Designs, 87
3.2 Randomized Block Designs, 90
3.3 Two-Way Layout: Factors with Fixed Levels, 94
   3.3.1 Two Qualitative Factors: A Regression Modeling Approach, 97
*3.4 Two-Way Layout: Factors with Random Levels, 99
3.5 Multi-Way Layouts, 108
3.6 Latin Square Designs: Two Blocking Variables, 110
3.7 Graeco-Latin Square Designs, 114
*3.8 Balanced Incomplete Block Designs, 115
*3.9 Split-Plot Designs, 120
3.10 Analysis of Covariance: Incorporating Auxiliary Information, 128
*3.11 Transformation of the Response, 133
3.12 Practical Summary, 137
Exercises, 138
Appendix 3A: Table of Latin Squares, Graeco-Latin Squares, and Hyper-Graeco-Latin Squares, 150
References, 152

4 Full Factorial Experiments at Two Levels 155
4.1 An Epitaxial Layer Growth Experiment, 155
4.2 Full Factorial Designs at Two Levels: A General Discussion, 157
4.3 Factorial Effects and Plots, 161
   4.3.1 Main Effects, 162
   4.3.2 Interaction Effects, 164
4.4 Using Regression to Compute Factorial Effects, 169
*4.5 ANOVA Treatment of Factorial Effects, 171
4.6 Fundamental Principles for Factorial Effects: Effect Hierarchy, Effect Sparsity, and Effect Heredity, 172
CONTENTS

6 Full Factorial and Fractional Factorial Experiments at Three Levels

6.1 A Seat-Belt Experiment, 267
6.2 Larger-the-Better and Smaller-the-Better Problems, 268
6.3 $3^k$ Full Factorial Designs, 270
6.4 $3^k-p$ Fractional Factorial Designs, 275
6.5 Simple Analysis Methods: Plots and Analysis of Variance, 279
6.6 An Alternative Analysis Method, 287
6.7 Analysis Strategies for Multiple Responses I: Out-of-Spec Probabilities, 293
6.8 Blocking in $3^k$ and $3^k-p$ Designs, 302
6.9 Practical Summary, 303

Exercises, 305
Appendix 6A: Tables of $3^k-p$ Fractional Factorial Designs, 312
Appendix 6B: Tables of $3^k-p$ Fractional Factorial Designs in $3^q$ Blocks, 313
References, 317

7 Other Design and Analysis Techniques for Experiments at More Than Two Levels

7.1 A Router Bit Experiment Based on a Mixed Two-Level and Four-Level Design, 319
7.2 Method of Replacement and Construction of $2^m 4^n$ Designs, 322
7.3 Minimum Aberration $2^m 4^n$ Designs with $n = 1, 2, 325
7.4 An Analysis Strategy for $2^m 4^n$ Experiments, 328
7.5 Analysis of the Router Bit Experiment, 330
7.6 A Paint Experiment Based on a Mixed Two-Level and Three-Level Design, 334
7.7 Design and Analysis of 36-Run Experiments at Two and Three Levels, 334
7.8 $r^k-p$ Fractional Factorial Designs for any Prime Number $r$, 341
   7.8.1 25-Run Fractional Factorial Designs at Five Levels, 342
   7.8.2 49-Run Fractional Factorial Designs at Seven Levels, 345
   7.8.3 General Construction, 345
*7.9 Related Factors: Method of Sliding Levels, Nested Effects Analysis, and Response Surface Modeling, 346
   7.9.1 Nested Effects Modeling, 348
   7.9.2 Analysis of Light Bulb Experiment, 350
   7.9.3 Response Surface Modeling, 353
7.9.4 Symmetric and Asymmetric Relationships Between Related Factors, 355
7.10 Practical Summary, 356
Exercises, 357
Appendix 7A: Tables of $2^m4^1$ Minimum Aberration Designs, 364
Appendix 7B: Tables of $2^m4^2$ Minimum Aberration Designs, 366
Appendix 7C: OA(25, 56), 368
Appendix 7D: OA(49, 78), 368
References, 370

8 Nonregular Designs: Construction and Properties 371
8.1 Two Experiments: Weld-Repaired Castings and Blood Glucose Testing, 371
8.2 Some Advantages of Nonregular Designs Over the $2^{k-p}$ and $3^{k-p}$ Series of Designs, 373
8.3 A Lemma on Orthogonal Arrays, 374
8.4 Plackett–Burman Designs and Hall’s Designs, 375
8.5 A Collection of Useful Mixed-Level Orthogonal Arrays, 379
*8.6 Construction of Mixed-Level Orthogonal Arrays Based on Difference Matrices, 381
  8.6.1 General Method for Constructing Asymmetrical Orthogonal Arrays, 382
*8.7 Construction of Mixed-Level Orthogonal Arrays Through the Method of Replacement, 384
8.8 Orthogonal Main-Effect Plans Through Collapsing Factors, 386
8.9 Practical Summary, 390
Exercises, 391
Appendix 8A: Plackett–Burman Designs OA(N, $2^{N-1}$) with 12 ≤ N ≤ 48 and N = 4k But Not a Power of 2, 397
Appendix 8B: Hall’s 16-Run Orthogonal Arrays of Types II to V, 401
Appendix 8C: Some Useful Mixed-Level Orthogonal Arrays, 405
Appendix 8D: Some Useful Difference Matrices, 416
Appendix 8E: Some Useful Orthogonal Main-Effect Plans, 418
References, 419

9 Experiments with Complex Aliasing 421
9.1 Partial Aliasing of Effects and the Alias Matrix, 421
9.2 Traditional Analysis Strategy: Screening Design and Main Effect Analysis, 424
9.3 Simplification of Complex Aliasing via Effect Sparsity, 424
CONTENTS

9.4 An Analysis Strategy for Designs with Complex Aliasing, 426
  9.4.1 Some Limitations, 432

*9.5 A Bayesian Variable Selection Strategy for Designs with Complex Aliasing, 433
  9.5.1 Bayesian Model Priors, 435
  9.5.2 Gibbs Sampling, 437
  9.5.3 Choice of Prior Tuning Constants, 438
  9.5.4 Blood Glucose Experiment Revisited, 439
  9.5.5 Other Applications, 441

*9.6 Supersaturated Designs: Design Construction and Analysis, 442

9.7 Practical Summary, 445
Exercises, 446
Appendix 9A: Further Details for the Full Conditional Distributions, 454
References, 456

10 Response Surface Methodology 459

10.1 A Ranitidine Separation Experiment, 459
10.2 Sequential Nature of Response Surface Methodology, 461
10.3 From First-Order Experiments to Second-Order Experiments: Steepest Ascent Search and Rectangular Grid Search, 464
  10.3.1 Curvature Check, 465
  10.3.2 Steepest Ascent Search, 466
  10.3.3 Rectangular Grid Search, 470
10.4 Analysis of Second-Order Response Surfaces, 473
  10.4.1 Ridge Systems, 475
10.5 Analysis of the Ranitidine Experiment, 477
10.6 Analysis Strategies for Multiple Responses II: Contour Plots and the Use of Desirability Functions, 481
10.7 Central Composite Designs, 484
10.8 Box–Behnken Designs and Uniform Shell Designs, 489
10.9 Practical Summary, 492
Exercises, 494
Appendix 10A: Table of Central Composite Designs, 505
Appendix 10B: Table of Box–Behnken Designs, 507
Appendix 10C: Table of Uniform Shell Designs, 508
References, 509
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>xiii</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>11 Introduction to Robust Parameter Design</strong></td>
<td>511</td>
</tr>
<tr>
<td>11.1 A Robust Parameter Design Perspective of the Layer Growth and Leaf Spring Experiments, 511</td>
<td></td>
</tr>
<tr>
<td>11.1.1 Layer Growth Experiment Revisited, 511</td>
<td></td>
</tr>
<tr>
<td>11.1.2 Leaf Spring Experiment Revisited, 512</td>
<td></td>
</tr>
<tr>
<td>11.2 Strategies for Reducing Variation, 514</td>
<td></td>
</tr>
<tr>
<td>11.3 Noise (Hard-to-Control) Factors, 516</td>
<td></td>
</tr>
<tr>
<td>11.4 Variation Reduction Through Robust Parameter Design, 518</td>
<td></td>
</tr>
<tr>
<td>11.5 Experimentation and Modeling Strategies I: Cross Array, 520</td>
<td></td>
</tr>
<tr>
<td>11.5.1 Location and Dispersion Modeling, 521</td>
<td></td>
</tr>
<tr>
<td>11.5.2 Response Modeling, 526</td>
<td></td>
</tr>
<tr>
<td>11.6 Experimentation and Modeling Strategies II: Single Array and Response Modeling, 532</td>
<td></td>
</tr>
<tr>
<td>11.7 Cross Arrays: Estimation Capacity and Optimal Selection, 535</td>
<td></td>
</tr>
<tr>
<td>11.8 Choosing Between Cross Arrays and Single Arrays, 538</td>
<td></td>
</tr>
<tr>
<td>*11.8.1 Compound Noise Factor, 542</td>
<td></td>
</tr>
<tr>
<td>11.9 Signal-to-Noise Ratio and Its Limitations for Parameter Design Optimization, 543</td>
<td></td>
</tr>
<tr>
<td>11.9.1 SN Ratio Analysis of Layer Growth Experiment, 546</td>
<td></td>
</tr>
<tr>
<td>*11.10 Further Topics, 547</td>
<td></td>
</tr>
<tr>
<td>11.11 Practical Summary, 548</td>
<td></td>
</tr>
<tr>
<td>Exercises, 550</td>
<td></td>
</tr>
<tr>
<td>References, 560</td>
<td></td>
</tr>
<tr>
<td><strong>12 Robust Parameter Design for Signal–Response Systems</strong></td>
<td>563</td>
</tr>
<tr>
<td>12.1 An Injection Molding Experiment, 563</td>
<td></td>
</tr>
<tr>
<td>12.2 Signal–Response Systems and Their Classification, 565</td>
<td></td>
</tr>
<tr>
<td>12.2.1 Calibration of Measurement Systems, 570</td>
<td></td>
</tr>
<tr>
<td>12.3 Performance Measures for Parameter Design Optimization, 571</td>
<td></td>
</tr>
<tr>
<td>12.4 Modeling and Analysis Strategies, 575</td>
<td></td>
</tr>
<tr>
<td>12.5 Analysis of the Injection Molding Experiment, 577</td>
<td></td>
</tr>
<tr>
<td>12.5.1 PMM Analysis, 580</td>
<td></td>
</tr>
<tr>
<td>12.5.2 RFM Analysis, 581</td>
<td></td>
</tr>
<tr>
<td>*12.6 Choice of Experimental Plans, 584</td>
<td></td>
</tr>
<tr>
<td>12.7 Practical Summary, 587</td>
<td></td>
</tr>
<tr>
<td>Exercises, 588</td>
<td></td>
</tr>
<tr>
<td>References, 596</td>
<td></td>
</tr>
</tbody>
</table>
13  Experiments for Improving Reliability 599
   13.1  Experiments with Failure Time Data, 599
      13.1.1  Light Experiment, 599
      13.1.2  Thermostat Experiment, 600
      13.1.3  Drill Bit Experiment, 600
   13.2  Regression Model for Failure Time Data, 604
   13.3  A Likelihood Approach for Handling Failure Time Data with Censoring, 605
      13.3.1  Estimability Problem with MLEs, 608
   13.4  Design-Dependent Model Selection Strategies, 609
   13.5  A Bayesian Approach to Estimation and Model Selection for Failure Time Data, 610
   13.6  Analysis of Reliability Experiments with Failure Time Data, 613
      13.6.1  Analysis of Light Experiment, 613
      13.6.2  Analysis of Thermostat Experiment, 614
      13.6.3  Analysis of Drill Bit Experiment, 615
   13.7  Other Types of Reliability Data, 617
   13.8  Practical Summary, 618
   Exercises, 619
   References, 623

14  Analysis of Experiments with Nonnormal Data 625
   14.1  A Wave Soldering Experiment with Count Data, 625
   14.2  Generalized Linear Models, 627
      14.2.1  The Distribution of the Response, 627
      14.2.2  The Form of the Systematic Effects, 629
      14.2.3  GLM versus Transforming the Response, 630
   14.3  Likelihood-Based Analysis of Generalized Linear Models, 631
   14.4  Likelihood-Based Analysis of the Wave Soldering Experiment, 634
   14.5  Bayesian Analysis of Generalized Linear Models, 635
   14.6  Bayesian Analysis of the Wave Soldering Experiment, 637
   14.7  Other Uses and Extensions of Generalized Linear Models and Regression Models for Nonnormal Data, 639
*14.8  Modeling and Analysis for Ordinal Data, 639
      14.8.1  The Gibbs Sampler for Ordinal Data, 642
*14.9  Analysis of Foam Molding Experiment, 644
14.10  Scoring: A Simple Method for Analyzing Ordinal Data, 647
CONTENTS

14.11 Practical Summary, 649
Exercises, 649
References, 661

Appendix A Upper Tail Probabilities of the Standard Normal Distribution, \( \int_{\xi}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-u^2/2} du \) 663

Appendix B Upper Percentiles of the \( t \) Distribution 665

Appendix C Upper Percentiles of the \( \chi^2 \) Distribution 667

Appendix D Upper Percentiles of the \( F \) Distribution 669

Appendix E Upper Percentiles of the Studentized Range Distribution 677

Appendix F Upper Percentiles of the Studentized Maximum Modulus Distribution 685

Appendix G Coefficients of Orthogonal Contrast Vectors 699

Appendix H Critical Values for Lenth’s Method 701

Author Index 705

Subject Index 709