

# CONTENTS

## Introduction / xiii

### ◀Chapter 1▶

#### **Introduction to Mechanical Analysis Using Finite Elements / 1**

- 1.1 Integrated Optomechanical Analysis Issues / 1
  - 1.1.1 Integration issues / 1
  - 1.1.2 Example: orbiting telescope / 1
  - 1.1.3 Example: lens barrel / 3
- 1.2 Elasticity Review / 4
  - 1.2.1 Three-dimensional elasticity / 4
  - 1.2.2 Two-dimensional plane stress / 6
  - 1.2.3 Two-dimensional plane strain / 8
  - 1.2.4 Principal stress and equivalent stress / 9
- 1.3 Basics of Finite Element Analysis / 10
  - 1.3.1 Finite element theory / 10
  - 1.3.2 Element performance / 12
  - 1.3.3 Structural analysis equations / 14
  - 1.3.4 Thermal analysis with finite elements / 16
  - 1.3.5 Thermal analysis equations / 17
- 1.4 Symmetry in FE models / 18
  - 1.4.1 General loads / 18
  - 1.4.2 Symmetric loads / 18
  - 1.4.3 Modeling techniques / 20
  - 1.4.4 Axisymmetry / 21
  - 1.4.5 Symmetry: pros and cons / 22
- 1.5 Stress Analysis / 22
  - 1.5.1 Stress models / 22
  - 1.5.2 Failure theories / 24
  - 1.5.3 Stress plots / 26
  - 1.5.4 Load envelopes / 26
- 1.6 Vibrations / 27
  - 1.6.1 Natural frequencies / 27
  - 1.6.2 Harmonic response / 27
  - 1.6.3 Random response / 29
  - 1.6.4 Damping / 30
- 1.7 Model Checkout / 31
- 1.8 Summary / 32
- References / 32

### ◀Chapter 2▶

#### **Optical Basics and Zernike Polynomials / 35**

- 2.1 Electromagnetic Basics / 35
- 2.2 Polarization / 36
- 2.3 Rays, Wavefronts, and Wavefront Error / 38

- 2.4 Image Quality and Optical Performance / 40
  - 2.4.1 Diffraction / 40
  - 2.4.2 Measures of image blur / 41
    - 2.4.2.1 Spot diagrams / 41
    - 2.4.2.2 Point spread function / 42
    - 2.4.2.3 Encircled energy function / 42
  - 2.4.3 Optical resolution / 43
  - 2.4.4 Modulation transfer function / 44
- 2.5 Image Formation / 46
  - 2.5.1 Spatial domain / 47
  - 2.5.2 Frequency domain / 48
- 2.6 Zernike Polynomials / 50
  - 2.6.1 Magnitude and phase / 56
  - 2.6.2 Orthogonality of Zernike polynomials / 57
    - 2.6.2.1 Noncircular apertures / 58
    - 2.6.2.2 Discrete data / 59
  - 2.6.3 Computing the Zernike polynomial coefficients / 60
- 2.7 Legendre-Fourier Polynomials / 61
- 2.8 Aspheric and x-y Polynomials / 62
- References / 63

### ◀Chapter 3▶

#### **Optomechanical Displacement Analysis Methods / 65**

- 3.1 Displacement Models of Optics / 65
  - 3.1.1 Definitions / 65
  - 3.1.2 Single point models / 67
  - 3.1.3 Solid optics / 68
    - 3.1.3.1 Two-dimensional models of solid optics / 68
    - 3.1.3.2 Three-dimensional element models of solid optics / 69
  - 3.1.4 Lightweight mirror models / 70
    - 3.1.4.1 Two-dimensional equivalent-stiffness models of lightweight mirrors / 71
    - 3.1.4.2 Three-dimensional equivalent-stiffness models / 76
    - 3.1.4.3 Three-dimensional plate/shell model / 79
    - 3.1.4.4 Example: gravity deformation prediction comparison of a lightweight mirror / 80
      - 3.1.4.4(a) Two-dimensional effective property calculations / 80
      - 3.1.4.4(b) Three-dimensional effective property calculations / 82
      - 3.1.4.4(c) Three-dimensional plate/shell model effective property calculations / 83
      - 3.1.4.4(d) Comparison of results / 83
  - 3.1.5 Generation of powered optic models / 85
- 3.2 Displacement Models of Adhesive Bonds / 86
  - 3.2.1 Elastic behavior of adhesives / 86
  - 3.2.2 Detailed three-dimensional solid model / 90
  - 3.2.3 Equivalent stiffness bond models / 90

- 3.2.3.1 Effective properties for “hockey-puck” type bonds / 91
- 3.2.3.2 Example: modeling of a hockey-puck type bond / 94
- 3.2.3.3 Effective properties for ring bonds / 96
- 3.3 Displacement Models of Flexures and Mounts / 99
  - 3.3.1 Classification of mounts / 99
  - 3.3.2 Modeling of kinematic mounts / 99
  - 3.3.3 Modeling of flexure mounts / 101
    - 3.3.3.1 Modeling of beam flexures / 101
    - 3.3.3.2 Example: modeling of bipod flexures / 104
    - 3.3.3.3 Modeling of blade flexures / 105
  - 3.3.4 Modeling of test supports / 107
    - 3.3.4.1 Modeling of air bags / 108
    - 3.3.4.2 Example: test support deformation analysis of a nonaxisymmetric optic / 111
    - 3.3.4.3 Modeling of V-block test supports / 115
    - 3.3.4.4 Modeling of sling and roller-chain test supports / 115
- 3.4 Displacement Analysis Methods / 116
  - 3.4.1 Analysis of surface effects / 116
    - 3.4.1.1 Composite-plate model / 116
    - 3.4.1.2 Homogeneous-plate model / 117
    - 3.4.1.3 Three-dimensional model / 119
    - 3.4.1.4 Example: coating-cure shrinkage / 120
      - 3.4.1.4(a) Composite-plate model / 120
      - 3.4.1.4(b) Homogenous plate model / 121
      - 3.4.1.4(c) Three-dimensional model / 121
  - 3.4.2 Analysis of assembly processes / 122
    - 3.4.2.1 Example: assembly analysis of mirror mounting / 124

References / 126

## <Chapter 4>

### **Integration of Optomechanical Analyses / 127**

- 4.1 Optical Surface Positional Errors / 127
- 4.2 Optical Surface Shape Changes / 129
  - 4.2.1 Optical surface deformations and wavefront error / 129
  - 4.2.2 Surface normal deformations / 131
  - 4.2.3 Sag deformations / 132
  - 4.2.4 Optical surface deformations and Zernike polynomials / 133
  - 4.2.5 Computing rigid-body motion from optical surface deformations / 135
  - 4.2.6 Representing shape changes in the optical model / 136
    - 4.2.6.1 Polynomial surface definition / 136
    - 4.2.6.2 Grid sag surface / 136
    - 4.2.6.3 Interferogram files / 136
    - 4.2.6.4 Interpolation / 137
  - 4.2.7 Focus, Zernike, and radius of curvature / 139
  - 4.2.8 Finite element derived spot diagrams / 140

- 4.3 Line-of-Sight Jitter / 140
  - 4.3.1 Computing image motion / 141
  - 4.3.2 Example: Cassegrain telescope / 142
  - 4.3.3 Quantifying the effects of jitter using the MTF / 144
    - 4.3.3.1 Constant velocity image motion / 145
    - 4.3.3.2 High-frequency sinusoidal image motion / 145
    - 4.3.3.3 Low-frequency sinusoidal image motion / 146
    - 4.3.3.4 Image jitter and the MTF for an airborne camera / 147
  - 4.3.4 Control system interaction / 147
- 4.4 Stress Birefringence / 148
  - 4.4.1 Mechanical stress and the index ellipsoid / 149
  - 4.4.2 Optical errors due to stress birefringence / 150
  - 4.4.3 Stress-optical coefficients / 153
  - 4.4.4 Nonuniform stress distributions / 154
  - 4.4.5 Example: stress birefringence / 156
  - 4.4.6 Stress birefringence and optical modeling / 158
- 4.5 Mechanical Obscurations / 160
  - 4.5.1 Obscuration periphery, area, and encircled energy / 160
  - 4.5.2 Diffraction effects for various spider configurations / 161
  - 4.5.3 Diffraction spikes / 162
  - References / 162

## ◀Chapter 5▶

### **Optothermal Analysis Methods / 165**

- 5.1. Thermo-Elastic Analysis / 165
  - 5.1.1 CTE temperature dependence / 165
  - 5.1.2 CTE inhomogeneity / 167
- 5.2 Thermo-Optic Analysis / 168
  - 5.2.1 Wavefront error / 169
  - 5.2.2 Sellmeier dispersion equation / 170
- 5.3 Effects of Temperature on Optical System Performance / 171
  - 5.3.1 Thermal soak conditions / 171
    - 5.3.1.1 Focus shift of a doublet lens / 172
  - 5.3.2 Radial gradients / 173
- 5.4 Optical Design Software / 174
  - 5.4.1 Representing OPD maps in the optical model / 174
- 5.5 Thermo-Optic Finite Element Models / 175
  - 5.5.1 Multiple reflecting surfaces / 176
- 5.6 Bulk Volumetric Absorption / 176
- 5.7 Mapping of Temperature Fields from the Thermal Model to the Structural Model / 178
  - 5.7.1 Nearest-node methods / 178
  - 5.7.2 Conduction analysis / 178
  - 5.7.3 Shape function interpolation / 179
- 5.8 Analogous Techniques / 179
  - 5.8.1 Moisture absorption / 180
  - 5.8.2 Adhesive curing / 180

References / 180

### ◀Chapter 6▶

#### **Adaptive Optics Analysis Methods / 183**

6.1 Introduction / 183

6.2 Method of Simulation / 184

6.2.1 Determination of actuator inputs / 186

6.2.2 Characterization metrics of adaptive optics / 186

6.2.2.1 Example: Adaptive control simulation of a mirror segment / 187

6.3 Coupled Adaptive Control Simulation and Structural Design Optimization / 9

6.3.1 Method of modeling actuators in design optimization / 190

6.3.2 Guidelines for adaptive control design optimization / 191

6.3.2.1 Example: Structural design of an adaptively controlled optic / 192

References / 193

### ◀Chapter 7▶

#### **Optimization of Optomechanical Systems / 195**

7.1 Overview / 195

7.2 Optimization Theory / 196

7.3 Structural Optimization, Including Optical Measures / 200

7.4 Integrated Thermal-Structural-Optical Optimization / 203

References / 205

### ◀Chapter 8▶

#### **Integrated Optomechanical Analysis of a Telescope / 207**

8.1 Overview / 207

8.2 Optical Model Description / 207

8.3 Structural Model Description / 208

8.4 One-Gravity Static Performance / 209

8.5 On-Orbit Image Motion Random Response / 209

8.6 Optimizing PMA with Optical Measures / 214

8.7 Adaptive PM / 215

8.8 System-level Multidisciplinary Optimization / 215

References / 217

### ◀Chapter 9▶

#### **Integrated Optomechanical Analysis of a Lens Assembly / 219**

9.1 Overview / 219

9.2 Thermal Analysis / 220

9.3 Thermo-elastic Analysis / 222

9.4 Stress Birefringence Analysis / 223

9.5 Thermo-Optic Analysis / 224

9.6 Optical Analysis / 224

**Index / 229**