Contents

Preface **xvii**
Contributors **xix**

Chapter 1. Newton, Fizeau, and Haidinger Interferometers **1**
M. V. Mantravadi and D. Malacara

1.1. Introduction 1
1.2. Newton Interferometer 1
1.2.1. Source and Observer's Pupil Size Considerations 9
1.2.2. Some Suitable Light Sources 11
1.2.3. Materials for the Optical Flats 12
1.2.4. Simple Procedure for Estimating Peak Error 12
1.2.5. Measurement of Spherical Surfaces 13
1.2.6. Measurement of Aspheric Surfaces 15
1.2.7. Measurement of Flatness of Opaque Surfaces 17
1.3. Fizeau Interferometer 17
1.3.1. The Basic Fizeau Interferometer 18
1.3.2. Coherence Requirements for the Light Source 20
1.3.3. Quality of Collimation Lens Required 22
1.3.4. Liquid Reference Flats 23
1.3.5. Fizeau Interferometer with Laser Source 23
1.3.6. Multiple-Beam Fizeau Setup 24
1.3.7. Testing Nearly Parallel Plates 26
1.3.8. Testing the Inhomogeneity of Large Glass or Fused Quartz Samples 27
1.3.9. Testing the Parallelism and Flatness of the Faces of Rods, Bars and Plates 28
1.3.10. Testing Cube Corner and Right-Angle Prisms 28
1.3.11. Fizeau Interferometer for Curved Surfaces 30
1.3.12. Testing Concave and Convex Surfaces 32
1.4. Haldinger Interferometer 33
1.4.1. Applications of Haidinger Fringes 35
1.4.2. Use of Laser Source for Haidinger Interferometer 36
1.4.3. Other Applications of Haidinger Fringes 39
1.5. Absolute Testing of Flats 40

COPYRIGHTED MATERIAL

Chapter 2. Twyman–Green Interferometer **46**
D. Malacara

2.1. Introduction 46
2.2. Beam-Splitter 48
2.2.1. Optical Path Difference Introduced by the Beam Splitter Plate 49
2.2.2. Required Accuracy in the Beam Splitter Plate 51
2.2.3. Polarizing Cube Beam Splitter 53
2.2.4. Nonpolarizing Cube Beam Splitter 55
2.3. Coherence Requirements 56
2.3.1. Spatial Coherence 56
2.3.2. Temporal Coherence 60
2.4. Uses of a Twyman–Green Interferometer 62
2.4.1. Testing of Prisms and Diffraction Rulings 64
2.4.2. Testing of Lenses 69
2.4.3. Testing of Microscope Objectives 71
2.5. Compensation of Intrinsic Aberrations in the Interferometer 72
2.6. Unequal-Path Interferometer 73
2.6.1. Some Special Designs 75
2.6.2. Improving the Fringe Stability 76
2.7. Open Path Interferometers 77
2.7.1. Mach-Zehnder Interferometers 77
2.7.2. Oblique Incidence Interferometers 78
2.8. Variations from the Twyman–Green Configuration 80
2.8.1. Multiple Image Interferometers 80
2.8.2. Interferometers with Diffractive Beam Splitters 80
2.8.3. Phase Conjugating Interferometer 81
2.9. Twyman–Green Interferograms and their Analysis 83
2.9.1. Analysis of Interferograms of Arbitrary Wavefronts 91

Chapter 3. Common-Path Interferometers **97**
S. Mallick and D. Malacara

3.1. Introduction 97
3.2. Burch's Interferometer Employing Two Matched Scatter Plates 98
3.2.1. Fresnel Zone Plate Interferometer 102
3.2.2. Burch and Fresnel Zone Plate Interferometers for Aspheric Surfaces 102
3.2.3. Burch and Fresnel Zone Plate Interferometers for Phase Shifting 102
3.3. Birefringent Beam Splitters 104
3.3.1. Savart Polariscope 104
3.3.2. Wollaston Prism 106
3.3.3. Double-Focus Systems 107
3.4. Lateral Shearing Interferometers 108
3.4.1. Use of a Savart Polariscope 108
3.4.2. Use of a Wollaston Prism 111

3.5. Double-Focus Interferometer 112
3.6. Saunders's Prism Interferometer 114
3.7. Point Diffraction Interferometer 116
3.8. Zernike Tests with Common-Path Interferometers 118

Chapter 4. Lateral Shear Interferometers 122
M. Strojnik, G. Paez, and M. Mantravadi

4.1. Introduction 122
4.2. Coherence Properties of the Light Source 123
4.3. Brief Theory of Lateral Shearing Interferometry 124
4.3.1. Interferograms of Spherical and Flat Wavefronts 126
4.3.2. Interferogams of Primary Aberrations upon Lateral Shear 128
4.4. Evaluation of an Unknown Wavefront 134
4.5. Lateral Shearing Interferometers in Collimated Light (White Light Compensated) 137
4.5.1. Arrangements Based on the Jamin Interferometer 137
4.5.2. Arrangements Based on the Michelson Interferometer 139
4.5.3. Arrangements Based on a Cyclic Interferometer 140
4.5.4. Arrangements Based on the Mach–Zehnder Interferometer 142
4.6. Lateral Shearing Interferometers in Convergent Light (White Light Compensated) 143
4.6.1. Arrangements Based on the Michelson Interferometer 143
4.6.2. Arrangements Based on the Mach–Zehnder Interferometer 146
4.7. Lateral Shearing Interferometers Using Lasers 149
4.7.1. Other Applications of the Plane Parallel Plate Interferometer 152
4.8. Other Types of Lateral Shearing Interferometers 157
4.8.1. Lateral Shearing Interferometers Based on Diffraction 158
4.8.2. Lateral Shearing Interferometers Based on Polarization 162
4.9. Vectorial Shearing Interferometer 164
4.9.1. Shearing Interferometry 165
4.9.2. Directional Shearing Interferometer 166
4.9.3. Simulated Interferometric Patterns 168
4.9.4. Experimental Results 173
4.9.5. Similarities and Differences With Other Interferometers 176

Chapter 5. Radial, Rotational, and Reversal Shear Interferometer 185
D. Malacara

5.1. Introduction 185
5.2. Radial Shear Interferometers 187
5.2.1. Wavefront Evaluation from Radial Shear Interferograms 189
5.2.2. Single-Pass Radial Shear Interferometers 190
5.2.3. Double-Pass Radial Shear Interferometers 195
5.2.4. Laser Radial Shear Interferometers 197
5.2.5. Thick-Lens Radial Shear Interferometers 202

5.3. Rotational Shear Interferometers 204
5.3.1. Source Size Uncompensated Rotational Shear Interferometers 207
5.3.2. Source Size Compensated Rotational Shear Interferometers 211
5.4. Reversal Shear Interferometers 211
5.4.1. Some Reversal Shear Interferometers 213

Chapter 6. Multiple-Beam Interferometers 219
C. Roychoudhuri

6.1. Brief Historical Introduction 219
6.2. Precision in Multiple-Beam Interferometry 221
6.3. Multiple-Beam Fizeau Interferometer 224
6.3.1. Conditions for Fringe Formation 224
6.3.2. Fizeau Interferometry 229
6.4. Fringes of Equal Chromatic Order 232
6.5. Reduction of Fringe Interval in Multiple-Beam Interferometry 235
6.6. Plane Parallel Fabry–Perot Interferometer 236
6.6.1. Measurement of Thin-Film Thickness 236
6.6.2. Surface Deviation from Planeness 237
6.7. Tolansky Fringes with Fabry–Perot Interferometer 241
6.8. Multiple-Beam Interferometer for Curved Surfaces 243
6.9. Coupled and Series Interferometers 244
6.9.1. Coupled Interferometer 245
6.9.2. Series Interferometer 246
6.10. Holographic Multiple-Beam Interferometers 247
6.11. Temporal Evolution of FP Fringes and Its Modern Applications 247
6.12. Final Comments 250

Chapter 7. Multiple-Pass Interferometers 259
P. Hariharan

7.1. Double-Pass Interferometers 259
7.1.1. Separation of Aberrations 259
7.1.2. Reduction of Coherence Requirements 262
7.1.3. Double Passing for Increased Accuracy 264
7.2. Multipass Interferometry 266

Chapter 8. Foucault, Wire, and Phase Modulation Tests 275
J. Ojeda-Castañeda

8.1. Introduction 275
8.2. Foucault or Knife-Edge Test 275
8.2.1. Description 275
8.2.2. Geometrical Theory 280
8.2.3. Physical Theory 289
8.3. Wire Test 293
8.3.1. Geometrical Theory 297

8.4. Platzeck–Gaviola Test 298
8.4.1. Geometrical Theory 299
8.5. Phase Modulation Tests 302
8.5.1. Zernike Test and its Relation to the Smart Interferometer 302
8.5.2. Lyot Test 305
8.5.3. Wolter Test 307
8.6. Ritchey–Common Test 310
8.7. Conclusions 313

Chapter 9. Ronchi Test 317
A. Cornejo-Rodriguez

9.1. Introduction 317
9.1.1. Historical Introduction 317
9.2. Geometrical Theory 318
9.2.1. Ronchi Patterns for Primary Aberrations 320
9.2.2. Ronchi Patterns for Aspherical Surfaces 327
9.2.3. Null Ronchi Rulings 328
9.3. Wavefront Shape Determination 331
9.3.1. General Case 333
9.3.2. Surfaces with Rotational Symmetry 335
9.4. Physical Theory 337
9.4.1. Mathematical Treatment 337
9.4.2. Fringe Contrast and Sharpness 340
9.4.3. Physical versus Geometrical Theory 343
9.5. Practical Aspects of the Ronchi Test 344
9.6. Some Related Tests 347
9.6.1. Concentric Circular Grid 347
9.6.2. Phase Shifting Ronchi Test 348
9.6.3. Sideband Ronchi Test 348
9.6.4. Lower Test 349
9.6.5. Ronchi–Hartmann and Null Hartmann Tests 350

Chapter 10. Hartmann, Hartmann–Shack, and Other Screen Tests 361
D. Malacara-Doblado and I. Ghozeil

10.1. Introduction 361
10.2. Some Practical Aspects 363
10.3. Hartmann Test Using a Rectangular Screen 366
10.4. Wavefront Retrieval 368
10.4.1. Tilt and Defocus Removal 368
10.4.2. Trapezoidal Integration 370
10.4.3. Southwell Algorithm 373
10.4.4. Polynomial Fitting 374
10.4.5. Other Methods 375

10.5. Hartmann Test Using a Screen with Four Holes 376
10.5.1. Four Holes in Cross 377
10.5.2. Four Holes in X 378
10.6. Hartmann Test of Ophthalmic Lenses 379
10.7. Hartmann Test Using Nonrectangular Screens 379
10.7.1. Radial Screen 380
10.7.2. Helical Screen 382
10.8. Hartmann–Shack Test 383
10.9. Crossed Cylinder Test 386
10.10. Testing with an Array of Light Sources or Printed Screens 387
10.10.1. Testing Convergent Lenses 388
10.10.2. Testing Concave and Convex Surfaces 389
10.11. Michelson–Gardner–Bennett Tests 393
10.12. Other Developments 394

Chapter 11. Star Tests 398
D. Malacara and W. T. Welford

11.1. Introduction 398
11.2. Star Test with Small Aberrations 399
11.2.1. The Aberration Free Airy Pattern 400
11.2.2. The Defocused Airy Pattern 403
11.2.3. Polychromatic Light 405
11.2.4. Systems with Central Obstructions 407
11.2.5. Effects of Small Aberrations 408
11.2.6. Gaussian Beams 409
11.2.7. Very Small Convergence Angles (Low Fresnel Numbers) 409
11.3. Practical Aspects with Small Aberrations 410
11.3.1. Effects of Visual Star Testing 410
11.3.2. The Light Source for Star Testing 412
11.3.3. The Arrangement of the Optical System for Star Testing 413
11.3.4. Microscope Objectives 415
11.4. The Star Test with Large Aberrations 416
11.4.1. Spherical Aberration 417
11.4.2. Longitudinal Chromatic Aberration 418
11.4.3. Axial Symmetry 418
11.4.4. Astigmatism and Coma 419
11.4.5. Distortion 419
11.4.6. Non-Null Tests 420
11.5. Wavefront Retrieval with Slope and Curvature Measurements 421
11.5.1. The Laplacian and Local Average Curvatures 421
11.5.2. Wavefront Determination with Iterative Fourier Transforms 422
11.5.3. Irradiance Transport Equation 425

11.6. Wavefront Determination with Two Images Using the Irradiance Transport Equation 426
11.7. Wavefront Determination with a Single Defocused Image Using Fourier Transform Iterations 429
11.8. Wavefront Determination with Two or Three Defocused Images Using Fresnel Transform Iterations 430

Chapter 12. Testing of Aspheric Wavefronts and Surfaces 435
D. Malacara, K. Creath, J. Schmit and J. C. Wyant

12.1. Introduction 435
12.2 Some Methods to Test Aspheric Wavefronts 437
12.3. Imaging of the Interference Pattern in Non-Null Tests 439
12.4. Some Null Testing Configurations 442
12.4.1. Flat and Concave Spherical Surfaces 442
12.4.2. Telescope Refracting Objectives 442
12.4.3. Concave Paraboloidal Surfaces 443
12.4.4. Concave Ellipsoidal or Spheroidal Surfaces 444
12.5. Testing of Convex Hyperboloidal Surfaces 445
12.5.1. Hindle Type Tests 445
12.5.2. Testing by Refraction 449
12.6. Testing of Cylindrical Surfaces 453
12.7. Early Compensators 454
12.7.1. Couder, Burch, and Ross Compensators 456
12.7.2. Dall Compensator 458
12.8. Refractive Compensators 461
12.8.1. Refractive Offner Compensator 462
12.8.2. Shafer Compensator 464
12.8.3. General Comments about Refracting Compensators 465
12.9. Reflecting Compensators 466
12.9.1. Reflective Offner Compensators 468
12.9.2. Reflective Adaptive Compensator 471
12.10. Other Compensators for Concave Conicoids 471
12.11. Interferometers Using Real Holograms 474
12.11.1. Holographic Wavefront Storage 476
12.11.2. Holographic Test Plate 476
12.12. Interferometers Using Synthetic Holograms 477
12.12.1. Fabrication of Computer-Generated Holograms (CGHs) 478
12.12.2. Using a CGH in an Interferometer 480
12.12.3. Off-Axis CGH Aspheric Compensator 483
12.12.4. In-Line CGH Aspheric Compensator 485
12.12.5. Combination of CGH with Null Optics 486
12.13. Aspheric Testing with Two-Wavelength Holography 488
12.14. Wavefront Stitching 491

12.14.1. Annular Zones 491
12.14.2. Circular Zones 493
12.14.3. Dynamic Tilt Switching 493

Chapter 13. Zernike Polynomial and Wavefront Fitting 498
Virendra N. Mahajan

13.1. Introduction 498
13.2. Aberrations of a Rotationally Symmetric System with a Circular Pupil 499
13.2.1. Power Series Expansion 499
13.2.2. Primary or Seidel Aberration Function 501
13.2.3. Secondary or Schwarzschild Aberration Function 504
13.2.4. Zernike Circle Polynomial Expansion 505
13.2.5. Zernike Circle Polynomials as Balanced Aberrations for Minimum Wave Aberration Variance 508
13.2.6. Relationships Between Coefficients of Power-Series and Zernike-Polynomial Expansions 510
13.2.7. Conversion of Seidel Aberrations into Zernike Aberrations 513
13.2.8. Conversion of Zernike Aberrations into Seidel Aberrations 515
13.3. Aberration Function of a System with a Circular Pupil, but Without an Axis of Rotational Symmetry 516
13.3.1. Zernike Circle Polynomial Expansion 516
13.3.2. Relationships Among the Indices n, m, and j 518
13.3.3. Isometric, Interferometric, and PSF Plots for a Zernike Circle Polynomial Aberration 520
13.3.4. Primary Zernike Aberrations and Their Relationships with Seidel Aberrations 521
13.4. Zernike Annular Polynomials as Balanced Aberrations for Systems with Annular Pupils 525
13.4.1. Balanced Aberrations 525
13.4.2. Zernike Annular Polynomials 525
13.4.3. Isometric, Interferometric, and PSF Plots for a Zernike Annular Polynomial Aberration 529
13.5. Determination of Zernike Coefficients From Discrete Wavefront Error Data 530
13.5.1. Introduction 530
13.5.2. Orthonormal Coefficients and Aberration Variance 535
13.5.3. Orthonormal Polynomials 537
13.5.4. Zernike Coefficients 538
13.5.5. Numerical Example 539
13.6. Summary 543

Chapter 14. Phase Shifting Interferometry **547**
Horst Schreiber and John H. Bruning

14.1. Introduction 547
14.2. Fundamental Concepts 548
14.3. Advantages of PSI 550
14.4. Methods of Phase Shifting 552
14.5. Detecting the Wavefront Phase 557
14.6. Data Collection 560
14.6.1. Temporal Methods 560
14.6.2. Spatial Methods 564
14.7. PSI Algorithms 568
14.7.1. Three Step Algorithms 569
14.7.2. Least-Squares Algorithms 571
14.7.3. Carré Algorithm 574
14.7.4. Family of Averaging Algorithms 576
14.7.5. Hariharan Algorithm 577
14.7.6. $2 + 1$ Algorithm 580
14.7.7. Methods to Generate Algorithms 582
14.7.8. Methods to Evaluate Algorithms 586
14.7.9. Summary of Algorithms 591
14.8. Phase Shift Calibration 596
14.9. Error Sources 599
14.9.1. Phase Shift Errors 600
14.9.2. Detector Nonlinearities 602
14.9.3. Source Stability 605
14.9.4. Quantization Errors 606
14.9.5. Vibration Errors 607
14.9.6. Air Turbulence 610
14.9.7. Extraneous Fringes and Other Coherent Effects 610
14.9.8. Interferometer Optical Errors 611
14.10. Detectors and Spatial Sampling 613
14.10.1. Solid State Sensors 613
14.10.2. Spatial Sampling 614
14.11. Quality Functions 617
14.11.1. Modulation 618
14.11.2. Residues 619
14.11.3. Filtering 622
14.12. Phase Unwrapping 623
14.12.1. Unwrapping in One Dimension 623
14.12.2. 2-D Phase Unwrapping 625
14.12.3. Path-Following Algorithms 626
14.12.4. Path Independent Methods 628
14.13. Aspheres and Extended Range PSI Techniques 629
14.13.1. Aliasing 630

14.13.2. Sub-Nyquist Interferometry 631
14.13.3. Two Wavelength PSI 635
14.13.4. Subaperture Stitching 637
14.14. Other Analysis Methods 638
14.14.1. Zero Crossing Analysis 638
14.14.2. Synchronous Detection 639
14.14.3. Heterodyne Interferometry 640
14.14.4. Phase Lock Interferometry 641
14.14.5. Spatial Synchronous and Fourier Methods 642
14.15. Computer Processing and Output 644
14.16. Implementation and Applications 647
14.16.1. Commercial Instrumentation 647
14.16.2. Interferometer Configurations 650
14.16.3. Absolute Calibration 651
14.16.4. Sources 654
14.16.5. Alignment Fiducials 655
14.17. Future Trends for PSI 655

Chapter 15. Surface Profilers, Multiple Wavelength, and White Light Intereferometry 667
J. Schmit, K. Creath, and J. C. Wyant

15.1. Introduction to Surface Profilers 667
15.1.1. Contact Profilometers 668
15.1.2. Optical Profilometers 668
15.1.3. Interferometric Optical Profilometers 668
15.1.4. Terms and Issues in Determining System Performance 669
15.2. Contact Profilometers 670
15.2.1. Stylus Profilers 670
15.2.2. Scanning Probe Microscopes 674
15.2.3. Comparison of AFM and Stylus Profiler 683
15.3. Optical Profilers 685
15.3.1. Optical Focus Sensors 687
15.3.2. Confocal Microscopy 689
15.4. Interferometric Optical Profilers 695
15.4.1. Common Features 696
15.5. Two Wavelength and Multiple Wavelength Techniques 702
15.5.1. Two-wavelengths Phase Measurement 704
15.5.2. Multiple-wavelength Phase Measurement 707
15.5.3. Reducing Measurement Time 710
15.6. White Light Interference Optical Profilers 711
15.6.1. White Light Interference 711
15.6.2. Image Buildup 712
15.6.3. Signal Processing of White Light Interferograms 713

15.6.4. Light Sources 716
15.6.5. Dispersion in White Light Fringes 716
15.6.6. Other Names for Interferometric Optical Profilers 723
15.7. Wavelength Scanning Interferometer 724
15.7.1. Wavelength Tunable Light Sources 724
15.7.2. Image Buildup 725
15.7.3. Signal Analysis 728
15.7.4. Film and Plate Thickness Measurement 729
15.8. Spectrally Resolved White Light Interferometry (SRWLI) 731
15.8.1. Image Buildup 731
15.8.2. Signal Analysis 732
15.8.3. Other Names for Spectral Interferometry 735
15.9. Polarization Interferometers 735
15.9.1. Differential Interference Contrast Microscope (Nomarski) 736
15.9.2. Geometric Phase Shifting 738
15.10. Optical Ranging Methods 741
15.10.1. Interferometric Ranging 741
15.10.2. Optical Triangulation 742
15.10.3. Time of Flight (TOF) 742
15.11. Summary 742

Chapter 16. Optical Metrology of Diffuse Surfaces 756
K. Creath, J. Schmit, and J. C Wyant

16.1. Moiré and Fringe Projection Techniques 756
16.1.1. Introduction 756
16.1.2. What is Moiré? 757
16.1.3. Moiré and Interferograms 762
16.1.4. Historical Review 768
16.1.5. Fringe Projection 769
16.1.6. Shadow Moiré 773
16.1.7. Projection Moiré 777
16.1.8. Two-angle Holography 778
16.1.9. Common Features 779
16.1.10. Comparison to Conventional Interferometry 779
16.1.11. Coded and Structured Light Projection 780
16.1.12. Applications 781
16.1.13. Summary 783
16.2. Holographic and Speckle Tests 783
16.2.1. Introduction 783
16.2.2. Holographic Interferometry for Nondestructive Testing 784
16.2.3. Speckle Interferometry and Digital Holography 791

Chapter 17. Angle, Prisms, Curvature, and Focal Length Measurements **808**
Z. Malacara

17.1. Introduction 808
17.2. Angle Measurements 808
17.2.1. Divided Circles and Goniometers 808
17.2.2. Autocollimator 810
17.2.3. Interferometric Measurements of Angles 812
17.3. Testing of Prisms 812
17.4. Radius of Curvature Measurements 817
17.4.1. Mechanical Measurement of Radius of Curvature 817
17.4.2. Optical Measurement of Radius of Curvature 820
17.5. Focal Length Measurements 823
17.5.1. Nodal Slide Bench 823
17.5.2. Focimeters 824
17.5.3. Other Focal Length Measurements 825

Chapter 18. Mathematical Representation of an Optical Surface and Its Characteristics **832**
D. Malacara

18.1. Definition of an Optical Surface 832
18.1.1. Parameters for Conic Surfaces 835
18.1.2. Some Useful Expansions of z 835
18.1.3. Aberration of the Normals to the Surface 836
18.2. Caustic Produced by an Aspheric Surface 837
18.3. Primary Aberrations of Spherical Surfaces 839
18.3.1. Spherical Aberration of and Aspherical Surface 839
18.3.2. Coma of a Concave Mirror 840
18.3.3. Astigmatism of a Concave Mirror 841
18.4. Astigmatic Surfaces 841
18.4.1. Toroidal Surface 842
18.4.2. Astigmatic Ellipsoidal and Oblate Spheroidal Surfaces 842
18.4.3. Sphero-Cylindrical Surface 844
18.4.4. Testing Astigmatic Surfaces and Reference Astigmatic Surface 846
18.4.5. Comparison Between Astigmatic Surfaces 847
18.5. Off-Axis Conicoids 849
18.5.1. Off-Axis Paraboloids 850

Appendix. Optical Testing Programs **852**

Index **855**