

# **Optical Measurement Techniques and Applications**

**Pramod K. Rastogi**  
**Editor**

Technische Universität Darmstadt FACHBEREICH INFORMATIK	
<b>B I B L I O T H E K</b>	
Inventar-Nr.:	900-00427
Sachgebiete:	
Standort:	

**Artech House, Inc.  
Boston • London**

---

# Contents

Preface	xv
Chapter 1 Introduction	1
1.1 Interference of Waves	3
1.2 Diffraction	5
1.3 Polarization	6
1.4 Speckle	8
1.5 Sensitivity, Accuracy, and Precision	9
1.6 Scope of the Text	10
1.7 Concluding Remarks	13
References	13
Chapter 2 Optical Metrology of Engineering Surfaces—Scope and Trends	15
2.1 Introduction	15
2.2 Triangulation	16
2.3 Projected Fringe Techniques for Industrial Inspection and Microshape Analysis	18
2.4 Interferometry for Precision Measurements	22
2.4.1 Two-Beam Interferometry	23
2.5 Interferometry on Optically Rough Surfaces	25
2.5.1 Interferometry at Oblique Incidence	25
2.5.2 Two-Wavelength Interferometry	26
2.5.3 Multiple-Wavelength Interferometry Together With Oblique Incidence	27
2.6 Shearing Interferometry	27
2.7 White-Light Interferometry for Micro- and Macrostructure Analysis	29

2.8	Heterodyne Interferometry	30
2.8.1	Super Heterodyne Interferometry	35
2.8.2	Super Heterodyne Interferometer With Rotational Matched Grating	38
2.9	Interferometry Outside the Coherence Length	41
2.10	Interferometry for Microtopography and Roughness Measurements	43
2.10.1	Heterodyne Interferometry for Microprofile Measurement	44
2.10.2	Scanning Differential-Heterodyne-Interferometer With Variable Base	44
	References	47
Chapter 3	Digital Processing of Fringe Patterns in Optical Metrology	51
3.1	Introduction	51
3.2	Techniques for Digital Phase Reconstruction	52
3.2.1	Methods for Preprocessing Fringe Patterns	54
3.2.2	Methods for Automatic Phase Measurement	62
3.2.3	Methods for Postprocessing Fringe Patterns	69
3.3	Measurement of Three-Dimensional Displacement Fields	78
3.4	Conclusion	80
	References	80
Chapter 4	Interferometric Optical Testing	87
4.1	Introduction	87
4.2	Principles of Optical Testing	87
4.2.1	A Classification of Testing Methods	87
4.2.2	The Diffraction Limit	88
4.2.3	The Real World	88
4.2.4	The Null Test	89
4.2.5	The Null Lens and the Computer-Generated Hologram	89
4.2.6	Principles of Interferometric Testing	91
4.3	Implementation and Development of Interferometric Testing Methods	93
4.3.1	Reference-Wavefront Interferometry	93
4.3.2	Common-Path Interferometry	101
4.3.3	Interferometric Testing of Nonoptical Surfaces	103
4.3.4	Modern Interferometers	103
4.3.5	Phase-Conjugate Interferometers	105
4.3.6	A Note on the Testing of Nonspherical Surfaces	106
4.4	Conclusion	107
	References	107
Chapter 5	Holographic Interferometry—An Important Tool in Nondestructive Measurement and Testing	111
5.1	Wavefront Reconstruction Process	112

---

5.2	Basic Methods of Wavefront Comparison	114
5.2.1	Double-Exposure Holography	114
5.2.2	Real-Time Holography	115
5.2.3	Sandwich Holography	117
5.2.4	Reflection Holography	118
5.3	Brief Introduction to Fringe Formation and Phase Difference Measurement	118
5.3.1	Fringe Localization	118
5.3.2	Image and Pupil Plane Decorrelations	119
5.3.3	Mapping of the Resolved Part of Displacement	119
5.3.4	Quantitative Measurement of Wavefront Phase Using Phase Shifting	121
5.4	Measurement of Static Deformation	122
5.4.1	Determination of Out-of-Plane Deformations	122
5.4.2	Measurement of an Out-of-Plane Rigid Body Rotation	123
5.4.3	Determination of In-Plane Displacements	124
5.4.4	Determination of the Derivatives of Displacement	127
5.4.5	Comparative Holography	128
5.5	Study of Vibrations	129
5.6	Flow Visualization	133
5.7	Measurement of Surface Topography	135
5.7.1	Two-Wavelength Contouring	136
5.7.2	Two-Refractive Index Contouring	137
5.7.3	Dual-Beam Multiple-Sources Contouring	137
5.7.4	Multiple-Sources Contouring	138
5.7.5	Multiple-Sources Slope Change Contouring	139
5.8	Concept of Holographic Flaw Detection	140
5.9	Some Examples of Application	140
5.10	TV Holography and Electronic Holography	144
5.11	Conclusions	146
	References	146
Chapter 6 Speckle Photography, Shearography, and ESPI		151
6.1	Introduction	151
6.2	Some Statistical Properties	152
6.3	Speckle Photography	153
6.3.1	Pointwise and Whole-Field Filtering Methods	153
6.3.2	Tilt Measurement	157
6.3.3	Rigid-Body Displacement Out-of-Plane	157
6.3.4	White-Light Speckle Photography	158
6.4	Speckle Interferometry	158
6.4.1	Sensitivity Vector	159

6.4.2	Out-of-Plane Sensitive Interferometer	161
6.4.3	Comparative Speckle Interferometry	162
6.4.4	In-Plane Displacement Measurement	163
6.5	Speckle-Shear Interferometry (Shearography)	165
6.5.1	Modified Michelson Arrangement	166
6.5.2	Double/Multiple-Aperture Methods	167
6.5.3	Radial and Rotational Shear	168
6.6	Contour Generation	169
6.7	ESPI	169
6.7.1	Background Concept	170
6.7.2	Applications of ESPI	173
6.7.3	Quantitative Evaluation	174
6.8	Summary	175
	References	177
<b>Chapter 7 Photoelasticity and Moiré</b>		183
7.1	Introduction	183
7.2	Photoelasticity	184
7.2.1	Introduction	184
7.2.2	Principle	185
7.2.3	Experimental Technique	186
7.2.4	Fringe Analysis and Processing	189
7.2.5	Advances and Applications	191
7.3	Moiré	197
7.3.1	Introduction	197
7.3.2	Principle	198
7.3.3	Advances and Applications	201
7.3.4	Moiré Interferometry	202
7.3.5	Computer-Aided Moiré Methods	205
7.4	Conclusions	213
	References	213
<b>Chapter 8 Optical Fiber Sensors</b>		217
8.1	Introduction	217
8.2	Intensity-Based Sensors	219
8.2.1	Transmissive Intensity-Based Sensors	220
8.2.2	Optrode Sensors	222
8.3	Distributed Sensors	226
8.3.1	Intrinsic Distributed Sensors	226
8.3.2	Quasi-Distributed Sensing	231
8.3.3	Fiber Bragg Grating Sensors	233
8.3.4	Bragg Grating Laser Sensors	238

---

8.4	Interferometric Sensors	239
8.4.1	Interferometric Configurations	240
8.4.2	Multiple-Beam Interferometers	243
8.4.3	Polarimetric Sensors	244
8.4.4	Low-Coherence Interferometry	245
8.4.5	Sensor Multiplexing	246
8.4.6	Applications of Interferometric Sensors	247
8.5	Summary	248
	References	248
Chapter 9 Fiber Optic Smart Sensing		255
9.1	Introduction	255
9.2	Fiber Optic Smart Sensing	256
9.3	Smart Sensing Subsystems	257
9.4	Sensor Selection	259
9.4.1	Strain, Deformation, and Displacement Measurements	259
9.4.2	Absolute and Relative Measurements	261
9.4.3	Dynamic, Short-Term, and Long-Term Measurements	262
9.4.4	Independent Measurement of Strain and Temperature	262
9.4.5	Multiplexing and Redundancy	263
9.4.6	Installation Techniques	263
9.5	Application Examples	265
9.5.1	Bridges	265
9.5.2	Curvature Measurements	269
9.6	Outlook	272
	References	273
Chapter 10 Holographic Metrology of Micro-objects in a Dynamic Volume		277
10.1	Introduction	277
10.2	Historical Background	278
10.3	Basic Principles of In-Line Fraunhofer Holography	279
10.3.1	Recording	280
10.3.2	Reconstruction	280
10.4	System Design Parameters	282
10.4.1	Film Resolution Requirement	283
10.4.2	Recording Range	284
10.4.3	Film Size and Source Coherence Requirements	284
10.4.4	Object Velocity and Exposure Time	284
10.4.5	Analysis of Reconstruction	285
10.4.6	Some Other Considerations and Limitations	285
10.5	Some Practical Considerations	286
10.5.1	Special Considerations With Recording Materials and Processes	286

10.5.2 Spatial Frequency Filtering	287
10.5.3 Transparent Objects	288
10.5.4 Finite Aperture Effects	288
10.5.5 Aberrations and Control	290
10.5.6 Cylindrical Test Sections	291
10.6 Hologram Fringe Contrast and Its Enhancement	292
10.7 Nonimage Plane Analysis	292
10.7.1 Analysis of the Hologram	292
10.7.2 Analysis by Misfocusing of the Image	292
10.7.3 Fourier Transform Analysis	293
10.8 Velocimetry and High-Speed Holography	293
10.9 Off-Axis Holography	294
10.10 Automated Analysis	294
10.11 Some Other Developments	294
10.11.1 Space-Related Applications	294
10.11.2 Cylindrical Holography and Other Unique Systems	295
References	296
 Chapter 11 Particle Image Velocimetry	305
11.1 Principles	305
11.1.1 Introduction to the Particle Image Velocimetry	305
11.1.2 The Development of Photographic Motion Arrestment Methods Used in PIV	305
11.1.3 The Development of PIV	306
11.1.4 Image Capture	308
11.1.5 Particle Dynamics	311
11.1.6 Lagrangian and Eulerian Descriptions of Fluid Motion	312
11.2 Methods of Image Analysis in PIV	313
11.2.1 The Young's Fringes Method	313
11.2.2 Correlation Methods	314
11.2.3 Spatial Filtering Techniques	316
11.2.4 The Analysis of Low Image-Density PIV Images	316
11.2.5 Velocity Bias	316
11.2.6 Automated Validation	317
11.2.7 Directional Ambiguity and Its Resolution	317
11.2.8 Viewing Angle Correction	318
11.2.9 Resolution, Precision, and Dynamic Range in PIV	319
11.3 Advances	319
11.3.1 Digital PIV (DPIV)	319
11.3.2 Cinematic PIV	320
11.3.3 Three-Component Methods	320
11.3.4 The Use of Color in PIV	324

---

11.3.5 Hardware Developments	324
11.3.6 Applications	327
11.4 Conclusions Highlighting Areas of Future Development	330
References	331
 Chapter 12 Surface Roughness Measurement	341
12.1 Introduction	341
12.2 Microscopy	346
12.3 Mechanical Profilers	349
12.4 Optical Profilers	350
12.5 Total Integrated Scattering	352
12.6 Angle-Resolved Scattering	355
12.7 Other Techniques	358
12.8 Importance of Surface Cleanliness	359
12.9 Future Developments	360
References	361
 Chapter 13 Lidar for Atmospheric Remote Sensing	369
13.1 Introduction	369
13.2 The Lidar Method	370
13.2.1 Scattering, Absorption, and Fluorescence	370
13.2.2 Lidar Equation	372
13.2.3 Solutions to the Lidar Equation	373
13.2.4 Differential Absorption	375
13.2.5 Raman Scattering	376
13.2.6 Raman/DIAL	378
13.2.7 Density and Temperature	379
13.3 Lidar Systems	380
13.3.1 NASA/CSFC Raman/DIAL Ozone Lidar System	380
13.3.2 Water Vapor Raman Lidar	387
13.3.3 Resonant Fluorescent Lidar	388
13.3.4 Doppler Lidar	389
13.4 Conclusion	390
References	391
Appendix 13A Nomenclature	396
 Chapter 14 Some Other Methods in Optical Metrology	399
14.1 Optical Caustics	399
14.1.1 Principle	399
14.1.2 Application	401
14.2 Digital Image Correlation	403
14.2.1 Correlation Methods for Planar Displacement Measurement	404

14.2.2 Deformation Gradients Measurements	404
14.2.3 Three-Dimensional Displacement Measurements	405
14.2.4 Conclusion	405
14.3 Ellipsometry	406
14.3.1 Principle	406
14.3.2 Techniques and Applications	408
14.4 Digital Photogrammetry	409
References	413
About the Authors	415
Index	421