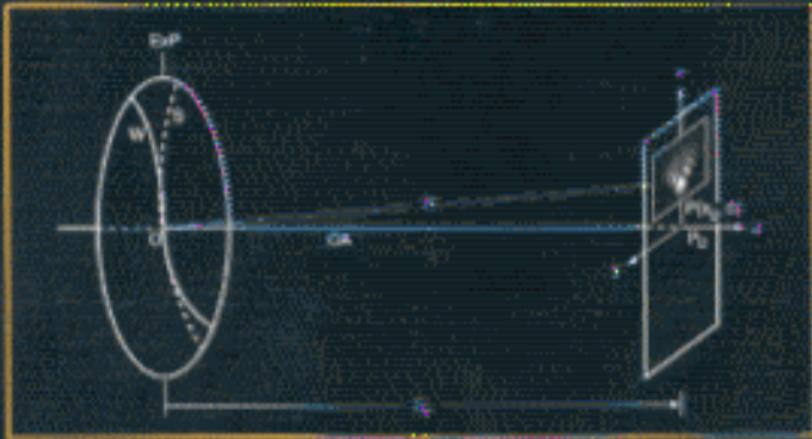


OPTICAL IMAGING AND ABERRATIONS

PART II

WAVE DIFFRACTION OPTICS



VIRENDRA N. MAHAJAN

TABLE OF CONTENTS

PART II. WAVE DIFFRACTION OPTICS

Preface	xv
Acknowledgments	xvii
Symbols and Notation.....	xix
CHAPTER 1: IMAGE FORMATION	1
1.1 Introduction	3
1.2 Rayleigh-Sommerfeld Theory of Diffraction and Huygens-Fresnel Principle	5
1.2.1 Rayleigh-Sommerfeld Formula.....	5
1.2.2 Fresnel and Fraunhofer Approximations	9
1.2.3 Transfer Function of Free Space	12
1.3 Gaussian Image	12
1.4 Diffraction Image	14
1.4.1 Pupil Function	14
1.4.2 Diffracted Wave	17
1.4.3 Incoherent PSF and Shift-Invariant Imaging of an Incoherent Object.....	22
1.5 Physical Significance of PSF	24
1.6 Optical Transfer Function (OTF)	27
1.6.1 General Relations	27
1.6.2 Physical Significance of OTF	31
1.6.3 Properties of OTF	33
1.6.4 OTF Slope at the Origin	35
1.6.5 OTF in the Limit of Zero Wavelength	40
1.6.6 Geometrical OTF	41
1.6.7 Comparison of Diffraction and Geometrical OTFs	44
1.6.8 Determination of OTF	45
1.6.9 Significance of PTF.....	45
1.7 Asymptotic Behavior of PSF	45
1.7.1 Point-Spread Function.....	46
1.7.2 Encircled Power	47
1.8 PSF Centroid	50
1.8.1 Centroid in Terms of OTF Slope	50
1.8.2 Centroid Related to Wavefront Slope	51
1.8.3 Centroid Related to Wavefront Perimeter	52
1.9 Strehl Ratio	53
1.9.1 General Relations	53
1.9.2 Approximate Expressions for Strehl Ratio.....	56
1.9.3 Determination of Strehl Ratio	58

1.10	Hopkins Ratio	59
1.11	Line- and Edge-Spread Functions (LSF and ESF)	61
1.11.1	Line-Spread Function	61
1.11.2	Edge-Spread Function	64
1.11.3	LSF and ESF in Terms of OTF	64
1.12	Shift-Invariant Imaging of a Coherent Object	67
1.12.1	Coherent Point-Spread Function	67
1.12.2	Coherent Transfer Function	69
1.13	Summary of Theorems.....	71
Appendix A: Fourier Transform Definitions		74
Appendix B: Some Frequently Used Integrals		75
References.....		76
Problems.....		78

CHAPTER 2: OPTICAL SYSTEMS WITH CIRCULAR PUPILS **79**

2.1	Introduction	81
2.2	Aberration-Free System	82
2.2.1	Point-Spread Function.....	82
2.2.2	Encircled Power	87
2.2.3	Ensquared Power	88
2.2.4	Excluded Power.....	90
2.2.5	Optical Transfer Function.....	93
2.2.6	PSF and Encircled Power From OTF	96
2.3	Strehl Ratio and Aberration Tolerance.....	97
2.3.1	Strehl Ratio.....	97
2.3.2	Primary Aberrations	98
2.3.3	Balanced Primary Aberrations	99
2.3.4	Comparison of Approximate and Exact Results	101
2.3.5	Rayleigh's $\lambda/4$ Rule	102
2.3.6	Strehl Ratio for Nonoptimally Balanced Aberrations	103
2.4	Balanced Aberrations and Zernike Circle Polynomials	105
2.5	Defocused System	110
2.5.1	Point-Spread Function.....	111
2.5.2	Focused Beam	113
2.5.3	Collimated Beam.....	119
2.6	PSFs for Rotationally Symmetric Aberrations	121
2.6.1	Theory	121
2.6.2	Numerical Results	124
2.6.3	Gaussian Approximation	134
2.6.4	Summary of Results	135

2.7	Symmetry Properties of an Aberrated PSF	136
2.7.1	General Theory	137
2.7.2	Symmetry About the Gaussian Image Plane	138
2.7.3	Symmetry of Axial Irradiance	141
2.8	PSFs for Primary Aberrations	142
2.8.1	Defocus	142
2.8.2	Spherical Aberration Combined with Defocus	142
2.8.3	Astigmatism Combined with Defocus	144
2.8.4	Coma	148
2.8.5	2-D PSFs	150
2.8.6	Comparison of Diffraction and Geometrical PSFs	157
2.9	Line of Sight of an Aberrated System	159
2.9.1	PSF and its Centroid	159
2.9.2	Numerical Results	162
2.9.2.1	Wavefront Tilt	162
2.9.2.2	Primary Coma	162
2.9.2.3	Secondary Coma	165
2.9.3	Comments	168
2.10	OTFs for Primary Aberrations	169
2.10.1	General Relations	169
2.10.2	Defocus	172
2.10.3	Spherical Aberration	173
2.10.4	Astigmatism	173
2.10.5	Coma	175
2.11	Hopkins Ratio	182
2.11.1	Tolerance for Primary Aberrations	182
2.11.2	Defocus	182
2.11.3	Hopkins Ratio in Terms of Variance of Aberration Difference Function	185
2.11.4	Variance of Aberration Difference Function for Primary Aberrations	186
2.12	Geometrical OTF	187
2.12.1	General Relations	188
2.12.2	Radially Symmetric Aberrations	189
2.12.3	Defocus	189
2.12.4	Spherical Aberration Combined with Defocus	190
2.12.5	Astigmatism Combined with Defocus	190
2.12.6	Coma	191
2.13	Incoherent Line- and Edge-Spread Functions	191
2.13.1	Theory	192
2.13.1.1	LSF From PSF	192
2.13.1.2	LSF From Pupil Function	192
2.13.1.3	Struve Ratio and Aberration Tolerances	193
2.13.1.4	LSF From OTF	196
2.13.1.5	ESF From OTF	198

2.13.2	Numerical Results	199
2.14	Miscellaneous Topics	205
2.14.1	Polychromatic PSF	205
2.14.2	Polychromatic OTF	208
2.14.3	Image of an Incoherent Disc	209
2.14.4	Pinhole Camera	218
2.15	Coherent Imaging.....	222
2.15.1	Coherent Spread Function	222
2.15.2	Coherent Transfer Function	223
2.15.3	Coherent LSF	224
2.15.4	Coherent ESF	229
2.15.5	Image of a Coherent Disc	234
2.15.6	Use of a Lens for Obtaining Fourier Transforms	238
2.15.7	Comparison of Coherent and Incoherent Imaging	241
References	253	
Problems.....	257	

CHAPTER 3: OPTICAL SYSTEMS WITH ANNULAR PUPILS 259

3.1	Introduction	261
3.2	Aberration-Free System.....	261
3.2.1	Point-Spread Function	261
3.2.2	Encircled Power	265
3.2.3	Ensquared Power	265
3.2.4	Excluded Power.....	266
3.2.5	Numerical Results	267
3.2.6	Optical Transfer Function.....	272
3.3	Strehl Ratio and Aberration Tolerance.....	281
3.3.1	Strehl Ratio	282
3.3.2	Primary Aberrations	283
3.3.3	Balanced Primary Aberrations	283
3.3.4	Comparison of Approximate and Exact Results	284
3.4	Balanced Aberrations and Zernike Annular Polynomials	291
3.5	Defocused System	298
3.5.1	Point-Spread Function.....	298
3.5.2	Focused Beam	299
3.5.3	Collimated Beam.....	303
3.6	Symmetry Properties of an Aberrated PSF	305
3.7	PSFs and Axial Irradiance for Primary Aberrations	308
3.8	2-D PSFs	311

3.9	Line of Sight of an Aberrated System	322
3.9.1	PSF and its Centroid	322
3.9.2	Numerical Results	323
3.9.2.1	Wavefront Tilt	323
3.9.2.2	Primary Coma	324
3.9.2.3	Secondary Coma	327
References.....		330
Problems.....		331

CHAPTER 4: OPTICAL SYSTEMS WITH GAUSSIAN PUPILS..... 333

4.1	Introduction	335
4.2	General Theory.....	336
4.3	Systems with Circular Pupils	337
4.3.1	Theory	337
4.3.2	Aberration-Free System	338
4.3.2.1	PSF	338
4.3.2.2	OTF	341
4.3.3	Strehl Ratio and Aberration Tolerance	343
4.3.4	Balanced Aberrations and Zernike-Gauss Circle Polynomials	344
4.3.5	Defocused System	348
4.3.5.1	Theory	348
4.3.5.2	Axial Irradiance	349
4.3.5.3	Defocused Distribution	350
4.3.5.4	Collimated Beam.....	352
4.3.6	Weakly Truncated Gaussian Circular Beams.....	353
4.3.6.1	Introduction	353
4.3.6.2	Irradiance Distribution and Beam Radius	354
4.3.6.3	Imaging of a Gaussian Beam.....	359
4.3.6.4	Aberration Balancing	362
4.3.7	Symmetry Properties of an Aberrated PSF	365
4.4	Systems with Annular Pupils.....	366
4.4.1	Theory	367
4.4.2	Aberration-Free System	368
4.4.3	Strehl Ratio and Aberration Tolerance	370
4.4.4	Balanced Aberrations and Zernike-Gauss Annular Polynomials	371
4.4.5	Defocused System	374
4.4.5.1	Theory	374
4.4.5.2	Axial Irradiance	374
4.4.5.3	Defocused Distribution	376
4.4.5.4	Collimated Beam.....	376
4.4.6	Symmetry Properties of an Aberrated PSF	378

4.5	Line of Sight of an Aberrated System	379
4.5.1	PSF and its Centroid	380
4.5.2	Numerical Results	380
4.5.2.1	Wavefront Tilt	380
4.5.2.2	Primary Coma	381
4.5.2.3	Secondary Coma	382
4.6	Summary	382
References		385
Problems		386
CHAPTER 5: RANDOM ABERRATIONS		387
5.1	Introduction	389
5.2	Random Motion.....	389
5.2.1	General Theory	390
5.2.2	Circular Pupils.....	391
5.2.2.1	Theory	391
5.2.2.2	Gaussian Approximation.....	392
5.2.2.3	Numerical Results	393
5.2.3	Annular Pupils.....	393
5.2.3.1	Theory	393
5.2.3.2	Numerical results	397
5.3	Imaging Through Atmospheric Turbulence.....	401
5.3.1	Long-Exposure Image	402
5.3.2	Kolmogorov Turbulence	407
5.3.3	Circular Pupils.....	413
5.3.4	Annular Pupils.....	417
5.3.5	Phase Aberration in Terms of Zernike Polynomials	421
5.3.6	Short Exposure Image	430
5.3.6.1	Near-Field Imaging	430
5.3.6.2	Far-Field Imaging	436
5.3.6.3	Short-Exposure Images	439
5.3.7	Adaptive Optics	441
Appendix: Fourier Transform of Zernike Polynomials		443
References		445
Problems		447
BIBLIOGRAPHY		449
REFERENCES FOR ADDITIONAL READING		451
INDEX		459