

Introduction to the Optical Transfer Function

CHARLES S. WILLIAMS

and

ORVILLE A. BECKLUND

Dallas, Texas



WILEY

A Wiley-Interscience Publication

John Wiley & Sons

New York / Chichester / Brisbane / Toronto / Singapore

Contents

1. OTF Historical Background	1
Introduction	1
The Early History of Optical Design and Image Evaluation	2
Laying the Foundation for OTF—1850 to 1940	6
The Appearance of Some Important Mathematics	8
Growing Awareness of OTF—The 1940s	9
Inventive OTF Instrumentation—The 1950s	10
Adjustment to Practice—The 1960s	13
Acceptance—The 1970s	15
The 1980s	16
Perspective	18
References	19
2. Concepts	23
Introduction	23
Spatial Frequency	23
Flux Density and Distributions	26
Frequency Spectrum	28
Three-Bar Pattern Spectrum	30
Even and Odd Harmonics and Functions	32
A Stepladder Bar Pattern	33
Spectrum for a General Distribution	35
Extension to Two Dimensions	37
Contrast and Contrast Transfer	38
Distributions of Physical Quantities	40
Point Sources	41
Stops and Pupils	42
Point Spread Functions	43
Spread Functions for Small Aberrations	50
Line Spread Functions	55
The Edge Trace	57
Isoplanatism	60
Linear Superposition	60

Coherence	61
References	62
3. Notation and Coordinates	64
Introduction	64
Sign and Nomenclature Conventions	66
Cardinal Points	66
Paraxial Notation	67
Need for Special Coordinates	69
Wave-Front Aberration	70
Nonparaxial Notation	73
Transfer Equations	78
Pupil Variables	80
Reduced Coordinates	81
Shifting the Image Plane	84
Magnification with Distortion	89
References	91
4. Diffraction Integral and Wave-Front Aberration Function	92
Introduction	92
Wave-Front Expressions and the Diffraction Integral	93
The Strehl Ratio	100
Anamorphic Stretching	101
The Pupil Function	102
The Wave Aberration Function	103
Power Series Expansion of the Wave Aberration Function	104
Spherical Aberration	108
Coma	115
Astigmatism	119
Curvature of Field	124
Distortion	124
Expansion of the Wave Aberration Function in Zernike Polynomials	126
References	131
5. Mathematical Theory of OTF	134
Introduction	134
Definitions, Nomenclature, and Conventions	135
Linearity and Isoplanatism	142
Image of a General Distribution	144
One-Dimensional Analysis	146

Optical Transfer Function	149
The Perfect OTF	152
Perfect OTF from Spread Function	158
Effects of Certain Aberrations on the Optical Transfer Function	162
Apodization	170
The Geometrical Optics OTF Approximation	177
The Polychromatic OTF	178
References	179
6. Optical Design and Image Criteria	181
The Nature of Optical Design	181
Automatic Lens Design	188
Selected Features of Design Programs	192
Manufacturing Tolerances	195
Assessment of Image Quality	196
Resolving Power versus Acutance	199
The Phase Transfer Function	204
References	208
7. Merit Functions and Aberration Balancing	211
Introduction	211
Single MTF Values and Certain Graphical Areas as Criteria of Performance	213
A Merit Function Based on the Low-Frequency End of the MTF	216
Other OTF-Related Merit Functions	217
Merit Evaluations Based on the Aberration Function	218
Mean Square Value of the Aberration Function as a Merit Function	218
Variance of the Aberration Function as a Merit Function	219
Variance of the Aberration Difference Function as a Merit Function	221
Aberration Balancing Based on the Power Series Expansion of the Wave Aberration Function	224
Aberration Balancing with Zernike Polynomials	234
Comparisons of Optimizing and Balancing Procedures	237
The Effect of Optical Parameter Variations on the Optical Transfer Function	240
References	244
8. Measurement	246
Introduction	246
Components of a Measuring System	249

Requirements of the Components	249
Direct Methods	255
Effect of Finite Grating Length	258
Changing Spatial Frequency	261
The Area Grating	263
Effect of Slit Width	268
Square Wave Gratings	270
Indirect Methods	272
Interferometric Methods	274
The Interferometer	275
An Interferometric Measuring Equipment	282
Other Interferometric Equipment	285
References	288
9. Calculation of the OTF: Analytical Methods	291
Introduction	291
The OTF Calculated for Defocusing	293
The OTF Calculated for Astigmatism	300
References	316
10. Calculation of the OTF: Numerical Methods	317
Introduction	317
Optical Path Difference Data by Interferometry	320
Calculation of the Aberration Polynomial	323
Extension to More Than One Independent Variable	325
Choice of Orthogonal Polynomial	326
Gauss Quadrature	329
References	335
Appendix A. Calculated Optical Transfer Functions	337
Introduction	337
Defocusing	337
Primary Spherical Aberration	338
Primary with Secondary Spherical Aberration	341
Primary and Secondary Coma with Defocusing	345
Spherical Aberration with Color	348
Optimum Balanced Fifth-Order Spherical Aberration	349
Primary Coma at Different Azimuths	354
Nonrotationally Symmetric Systems	357
References	360

Appendix B: Some Mathematics	362
The Fourier Transform	362
The Delta Function	365
The Convolution Integral	367
Convolution Identities	369
Convolution Integral When One Function Is Sinusoidal	370
Significance of the Convolution Integral	372
Convolution and Spread Functions	378
Other Convolution Integrals	379
The Correlation Function	380
Examples	381
References	386
Appendix C: Diffraction Integral Fundamentals	387
Introduction	387
The Traveling Wave Equation	387
Spherical Wave-Fronts	391
Application of the Huygens–Fresnel Principle to a Spherical Wave-Front	395
Application of the Huygens–Fresnel Principle to Chapter 4	398
References	400
INDEX	401