

Contents

Acknowledgements ix

1 Introduction 1

1.1 Motivation for Revisiting Aero-Optics 2

2 Fundamentals 7

2.1 Wavefronts and Index of Refraction 7

2.2 Huygens' Principle 8

2.3 Basic Equations and Optical Path Difference 11

2.4 Linking Equation 15

2.5 Image at a Focal Plane (Far-field Propagation) 17

2.6 Far-field Intensity in the Presence of Near-field Distortions 20

2.6.1 Temporal Intensity Variation 25

2.7 Wavefront Components 26

3 Measuring Wavefronts 31

3.1 Interferometry Methods 31

3.2 Wavefront Curvature Methods 33

3.3 Gradient-based Wavefront Sensors 35

3.3.1 Shack-Hartmann Wavefront Sensor 37

3.3.1.1 Wavefront Reconstruction Algorithm 41

3.3.2 Malley Probe 43

3.3.3 SABB Sensor 46

3.4 Typical Optical Set-Ups 47

4 Data Reduction and Interpretation 55

4.1 Statistical Analysis 56

4.1.1 Temporal and Spatial OPD_{rms} 56

4.1.2 Histograms and Higher-Moment Statistics 58

4.2	Spectral Analysis	60
4.2.1	Relation between the Deflection Angle Spectrum and the Wavefront Statistics	62
4.2.2	Dispersion Analysis	63
4.3	Modal Analysis	65
4.3.1	Zernike Functions	66
4.3.2	Proper Orthogonal Decomposition (POD)	70
4.3.2.1	Direct Method	73
4.3.2.2	Snapshot Method	74
4.3.3	Dynamic Mode Decomposition (DMD)	82
4.4	Cross-correlation-based Techniques	85
4.4.1	Local Convective Speeds	85
4.4.2	Multi-point Malley Probe Analysis	89
4.4.3	Spatially Varying 2-D Convective Velocity	92
5	Aperture Effects	97
6	Typical Aero-Optical Flows	105
6.1	Scaling Arguments	105
6.2	Free Shear Layers	106
6.2.1	Shear-Layer Physics	106
6.2.2	Aero-Optical Effects	109
6.2.3	Historical Shear Layer Measurements in AEDC	110
6.2.4	Weakly Compressible Model	114
6.3	Boundary Layers	118
6.3.1	Model of Aero-optical Distortions for Boundary Layers with Adiabatic Walls	122
6.3.2	Angular Dependence	130
6.3.3	Finite Aperture Effects	132
6.3.4	Nonadiabatic Wall Boundary Layers	133
6.3.5	Instantaneous Far-Field Intensity Drop-Outs	142
6.3.5.1	Absolute SR Threshold	147
6.3.5.2	Relative Intensity Variation	150
6.4	Turrets	152
6.4.1	AAOL	154
6.4.2	Flow Topology and Dynamics	159
6.4.3	Steady-lensing Effects at Forward-looking Angles	167
6.4.4	Aero-optical Environment at Back-looking Angles	169
6.4.5	Shock-effects at Transonic Speeds	172

7	Aero-Optical Jitter	179
7.1	Local and Global Jitter	180
7.1.1	Local Jitter	180
7.1.2	Global Jitter	180
7.2	Subaperture Effects	183
7.3	Techniques to Remove the Mechanically Induced Jitter	183
7.3.1	Cross-correlation Techniques	184
7.3.2	Large-Aperture Experiments	186
7.3.3	Stitching Method	187
8	Applications to Adaptive Optics	195
8.1	Beam-Control Components	195
8.2	How Much Correction Is Needed	198
8.3	Flow-Control Mitigation	198
8.3.1	Non-Flow-Control Mitigation	199
8.3.2	Some Qualities of Separated Shear Layers	200
8.3.3	Using the POD Analysis to Develop Requirements	204
8.4	Proper Number of Wavefront Sensor Subapertures to Actuator Ratio	208
8.4.1	Numerical Simulation	209
8.4.2	Simulation Results	211
8.4.3	Conclusion from the Simulation Results	213
9	Adaptive Optics for Aero-Optical Compensation	217
9.1	Analogies from Free-Stream Turbulence Compensation	217
9.1.1	Statistical Optics Theoretical Considerations	217
9.1.2	Power-Law Observations from Aero-Optical Wavefront Data	219
9.2	Compensation Scaling Laws for Aero-Optics	222
9.2.1	Adaptive Optics Control Law and Error Rejection Transfer Function	222
9.2.2	Asymptotic Results for Aero-Optics Compensation	223
9.2.3	Aero-Optics Compensation Frequency	225
9.2.4	Relation of Aero-Optics Scaling Laws to Free-Stream Turbulence	227
9.3	Spatial and Temporal Limitations of Adaptive Optics	228
9.3.1	Framework for Analysis of Aero-Optical Compensation	228
9.3.2	Deformable Mirror Fitting Error for Aero-Optical POD Modes	229
9.3.3	Decomposition of Correctable and Uncorrectable Power Spectrum	233
9.3.3.1	DM Sensitivity Transfer Function	233
9.3.4	Closed-Loop Residual Wavefront Error	234

9.3.5	Effect of Latency in Aero-Optics Compensation	236
9.4	Application to System Performance Modeling	238
9.4.1	Scaling of Aero-Optical Statistics to Flight Conditions	239
9.4.2	Joint Variations in Adaptive Optics Bandwidth and Actuator Density	239
9.4.3	Relative Impact of Aero-Optics with Other Propagation and System Effects	244
9.4.3.1	Comparing Aero-Optics to Free-Stream Turbulence Propagation	245
9.4.3.2	Comparing Aero-Optics to System Optical Jitter	246
9.4.4	Tracker Performance Degradations Related to Aero-Optics	248
9.4.4.1	Track Sensor Aero-Optical Imaging Resolution Degradation	249
9.4.4.2	Illuminator Propagation and Active Imaging through Aero-Optics	250
10	Concluding Remarks	255
	References	259
	Index	271