

Contents

Notation	xix
1 Introduction	1
1.1 Surface and Roundness Metrology	1
1.2 Scope and Objectives	1
1.3 Organization	3
References	4
Part I Filtering	
2 A Brief History of Filtering	7
2.1 Introduction	7
2.2 Electrical Filters	7
2.3 Digital Filters	8
2.4 The Envelope Method	8
2.5 The Gaussian Filter	8
2.6 Overlap of Measurement Techniques	9
2.7 Recent Advances in Filtering	9
2.8 Summary	10
References	10
3 Filtering in the Frequency Domain	13
3.1 Surface Wavelengths	13
3.2 Fourier Transform, Discrete Fourier Transform, and Fast Fourier Transform	14
3.3 Filtering in the Frequency Domain	16
3.4 Wrap-Around Effect	19
3.5 Amplitude Transmission and Phase Characteristics	19
3.6 Summary	20
Exercises	20
References	21

4	Filtering in the Time Domain	23
4.1	Filtering as an Averaging Process	23
4.2	Relationship Between Frequency-Domain and Time-Domain Filtering	26
4.3	Filtering Profiles: Putting It All Together	27
4.4	Summary	29
	Exercises	30
	References	31
5	Gaussian Filter	33
5.1	Introduction	33
5.2	High-Pass and Low-Pass Filters	35
5.3	Roughness, Waviness, and Form Using the Gaussian Filter	35
5.4	Effect of Cutoff	36
5.5	Phase Characteristics	36
5.6	Summary	37
	Exercises	37
	References	38
6	The 2RC Filter	39
6.1	Introduction	39
6.2	The 2RC High-Pass Filter	39
6.3	More on the 2RC Filter	42
6.4	Comparison of the 2RC and Gaussian Filters	44
6.5	Summary	44
	Exercises	45
	References	46
7	Filtering Roundness Profiles	47
7.1	Introduction	47
7.2	Gaussian Filter for Roundness	47
7.3	Amplitude Transmission Characteristics	49
7.4	Filtering Roundness Profiles in the Time Domain	50
7.5	Circular Convolution in the Frequency Domain	50
7.6	Summary	52
	Exercises	52
	References	53
8	Filtering 3D Surfaces	55
8.1	Areal Surface Texture Analysis	55
8.2	2D Convolution	55
8.3	Gaussian Filter in 3D	56
8.4	A Note on Indices	56
8.5	Frequency-Domain Filtering in 3D	59
8.6	Summary	62
	Exercises	62
	References	63

Part II Advanced Filtering

9	Gaussian Regression Filters	67
9.1	Introduction	67
9.2	Zero-Order Gaussian Regression Filter	68
9.3	Second-Order Gaussian Regression Filter	71
9.4	3D Zero-Order Gaussian Regression Filter	73
9.5	3D Second-Order Gaussian Regression Filter	74
9.6	Summary	75
	Exercises	75
	References	76
10	Spline Filter	77
10.1	Introduction	77
10.2	Amplitude Transmission Characteristics	78
10.3	Implementation of the Non-periodic Spline Filter	79
10.4	Implementation of the Periodic Spline Filter	82
10.5	Summary	86
	Exercises	86
	References	86
11	Robust Filters	87
11.1	Rk Filter	87
11.2	Robust Gaussian Regression Filter	90
11.3	Summary	91
	Exercises	92
	References	92
12	Envelope and Morphological Filters	93
12.1	Envelope Filters	93
12.2	Stylus Tip Convolution	94
12.3	Morphological Filters	96
12.4	A Word on the Fundamentals	98
12.5	3D Morphological Filtering	98
12.6	Summary	100
	Exercises	100
	References	101
13	Multi-scale Filtering	103
13.1	Introduction	103
13.2	Alternate Sequence Filters or Scale Space Analysis	103
13.3	Wavelet-Based Filters	107
13.4	Summary	109
	Exercises	110
	References	111

Part III Fitting

14	Introduction to Fitting Substitute Geometry	115
14.1	Introduction	115
14.2	Fitting Criteria	116
14.3	Solution Methodologies	117
	References	118
15	Least-Squares Best-Fit Line and Plane	121
15.1	Introduction	121
15.2	Closed-Form Solution for LS Best-Fit Line	121
15.3	Matrix Formulation	122
15.4	Centroid as a Point on the LS Line	123
15.5	Normal LS in Parametric Form	124
15.6	Lagrange Multiplier Method	126
15.7	Back to the LS Line	127
15.8	LS Best-Fit Plane	128
15.9	Summary	129
	Exercises	129
	References	130
16	Non-linear Least-Squares I: Introduction	131
16.1	Introduction	131
16.2	Formulating the Circle in a Plane Problem	131
16.3	The Steepest Descent Algorithm	132
16.4	The Gauss–Newton Algorithm	134
16.5	The Levenberg–Marquardt Algorithm	136
16.6	Summary	137
	Exercises	138
	References	138
17	Non-linear Least-Squares II: Circle, Sphere, and Cylinder	139
17.1	Introduction	139
17.2	Initial Estimates for Center and Radius of Circle	139
17.3	Best-Fit Sphere	142
17.4	Best-Fit Cylinder	143
17.5	Summary	144
	Exercises	144
	References	144
18	Fitting Radius-Suppressed Circle Data	145
18.1	Introduction	145
18.2	The Limaçon Approximation	145
18.3	LS Best-Fit Circle	146
18.4	LS Best-Fit Cylinder	148
18.5	Errors in the Limaçon Approximation	149

18.6	Summary	150
	Exercises	151
	References	151
19	Exchange Algorithms for Minimum Zone	153
19.1	Introduction	153
19.2	Exchange Algorithms	153
19.3	Exchange Algorithm for Line	154
19.4	Exchange Algorithm for Plane	157
19.5	Exchange Algorithm for Circle	159
19.6	Summary	162
	Exercises	163
	References	163
20	Reference Circle-Fitting Using Linear Programming Simplex	165
20.1	Introduction	165
20.2	LP Simplex	165
20.3	Formulating the MI Problem	167
20.4	Formulating the MC Problem	171
20.5	Duality	172
20.6	LP and Exchange Algorithms	174
20.7	Exchange Algorithms for MI and MC Circles	176
20.8	Summary	176
	Exercises	176
	References	177

Part IV Parameterization

21	Surface Finish Parameters I:	
	Amplitude, Spacing, Hybrid, and Shape	181
21.1	Introduction	181
21.2	Amplitude Parameters	181
21.3	Spacing Parameters	183
21.4	Hybrid and Shape Parameters	186
21.5	Summary	188
	Exercises	189
	References	190
22	Surface Finish Parameters II:	
	Autocorrelation, Power Spectral Density, Bearing Area	191
22.1	Autocovariance and Autocorrelation Function	191
22.2	Power Spectral Density	193
22.3	Amplitude Density Function and Bearing Area Curve	195
22.4	Summary	198
	Exercises	199
	References	199

23	3D Surface Texture Parameters	201
23.1	Introduction	201
23.2	Amplitude and Shape Parameters	201
23.3	AACV, APSD, and BAC for 3D Surfaces	202
23.4	Spacing and Hybrid Parameters	205
23.5	Summary	206
	Exercises	206
	References	206
 Part V Errors and Uncertainty		
24	Uncertainty Considerations	209
24.1	Introduction	209
24.2	Random and Systematic Components	209
24.3	Uncertainty Modeling	210
24.4	Uncertainty Propagation	210
24.5	Systematic Errors: an Example	210
	References	211
25	Uncertainty Propagation in Computations	213
25.1	Introduction	213
25.2	Intervals at Some Level of Confidence	214
25.3	The Central Limit Theorem	215
25.4	Limitations of GUM	217
25.5	The Monte Carlo Method	217
25.6	Filtering Surface Profiles	218
25.7	Fitting Substitute Geometry	221
25.8	Summary	223
	Exercises	224
	References	224
26	Error Separation Techniques in Roundness Metrology	225
26.1	Introduction	225
26.2	Full Reversal	225
26.3	Two-Position Method	226
26.4	Two-Probe Method	229
26.5	Three-Probe FFT Method	229
26.6	Three-Probe Sequential Method	231
26.7	Three-Position FFT Method	233
26.8	Error Separation by Solving Linear Equations	234
26.9	Uncertainty Propagation	236
26.10	Summary	236
	Exercises	236
	References	237

27 Other Relevant Topics 239

 27.1 Introduction 239

 27.2 Parameter Extraction..... 239

 27.3 Tools for Correlation and Diagnostics 240

 27.4 Challenges 241

 References 241

Answers to Selected Exercises..... 243

Index 261