Speckle Phenomena in Optics Theory and Applications

Joseph W. Goodman

R O B E R T S & C O M P A N Y Englewood, Colorado

Contents

	Pref	ace	ix
1	Ori	gins and Manifestations of Speckle	1
	1.1	General Background	1
	1.2	Intuitive Explanation of the Cause of Speckle	2
	1.3	Some Mathematical Preliminaries	5
2	Ran	dom Phasor Sums	7
	2.1	First and Second Moments of the Real and Imaginary Parts of the Resultant Phasor	8
	22	Random Walk with a Large Number of Independent Steps	10
	2.3	Random Phasor Sum Plus a Known Phasor	13
	2.4	Sums of Random Phasor Sums	17
	2.5	Finite Number of Equal Length Components	17
	2.6	Nonuniform Distribution of Phases	19
3	First-Order Statistical Properties		
	3.1	Definition of Intensity	25
	3.2	First-Order Statistics of the Intensity and Phase	27
		3.2.1 Large Number of Random Phasors	27
		3.2.2 Constant Phasor plus a Random Phasor Sum	30
		3.2.3 Finite Number of Equal-Length Phasors	34
	3.3	Sums of Speckle Patterns	37
		3.3.1 Sums on an Amplitude Basis	38
		3.3.2 Sum of Two Independent Speckle Intensities	- 38

		3.3.3	Sum of N Independent Speckle Intensities	42			
		3.3.4	Sums of Correlated Speckle Intensities	44			
	3.4	Partia	Ily Polarized Speckle	47			
	3.5	Partia	lly Developed Speckle	50			
	3.6	Speck	led Speckle, or Compound Speckle Statistics	53			
		3.6.1	Speckle Driven by a Negative Exponential Intensity				
			Distribution	54			
		3.6.2	Speckle Driven by a Gamma Intensity Distribution	55			
		3.6.3	Sums of Independent Speckle Patterns Driven by a Gamma				
			Intensity Distribution	57			
4	Higher-Order Statistical Properties of Speckle						
	4.1	Multiv	variate Gaussian Statistics	59			
	4.2	Applic	cation to Speckle Fields	60			
	4.3	Multic	limensional Statistics of Speckle	62			
	0.00	4.3.1	Joint Density Function of the Amplitudes	64			
		4.3.2	Joint Density Function of the Phases	65			
		4.3.3	Joint Density Function of the Intensities.	68			
	4.4	Autoc	orrelation Function and Power Spectrum of Speckle	73			
		4.4.1	Free-Space Propagation Geometry	73			
		4.4.2	Imaging Geometry	80			
		4.4.3	Speckle Size in Depth	82			
	4.5	Depen	Idence of Speckle on Scatterer Microstructure	84			
		4.5.1	Surface vs. Volume Scattering	85			
		4.5.2	Effect of a Finite Correlation Area of the Scattered Wave	85			
		4.5.3	A Regime where Speckle Size Is Independent of Scattering				
			Spot Size	90			
		4.5.4	Relation between the Correlation Areas of the Scattered Wave				
			and the Surface Height Fluctuations-Surface Scattering	92			
		4.5.5	Dependence of Speckle Contrast on Surface Roughness-Surface				
			Scattering	98			
		4.5.6	Properties of Speckle Resulting from Volume Scattering	102			
	4.6	Statist	ics of Integrated and Blurred Speckle	105			
		4.6.1	Mean and Variance of Integrated Speckle	106			
		4.6.2	Approximate Result for the Probability Density Function of				
			Integrated Intensity	111			
		4.6.3	"Exact" Result for the Probability Density Function of				
			Integrated Intensity	113			
		4.6.4	Integration of Partially Polarized Speckle Patterns	118			
	4.7	Statist	ics of Derivatives of Speckle Intensity and Phase	120			
		4.7.1	Background	121			
		4.7.2	Parameters for Various Scattering Spot Shapes	123			

		4.7.3	Derivatives of Speckle Phase: Ray Directions in a Speckle			
			Pattern	124		
		4.7.4	Derivatives of Speckle Intensity	127		
		4.7.5	Level Crossings of Speckle Patterns	130		
	4.8	Zeros o	of Speckle Patterns: Optical Vortices	133		
		4.8.1	Conditions Required for a Zero of Intensity to Occur	133		
		4.8.2	Properties of Speckle Phase in the Vicinity of a Zero of			
			Intensity	133		
		4.8.3	The Density of Vortices in Fully Developed Speckle	136		
		4.8.4	The Density of Vortices for Fully Developed Speckle Plus a			
			Coherent Background	138		
5	Optical Methods for Suppressing Speckle					
	5.1	Polariz	ation Diversity	142		
	5.2	Tempo	ral Averaging with a Moving Diffuser.	143		
		5.2.1	Background	143		
		5.2.2	Smooth Object	149		
		5.2.3	Rough Object	151		
	5.3	Wavele	ength and Angle Diversity	153		
		5.3.1	Free-Space Propagation, Reflection Geometry	154		
		5.3.2	Free-Space Propagation, Transmission Geometry	164		
		5.3.3	Imaging Geometry	167		
	5.4	Tempo	and Spatial Coherence Reduction	170		
	17013	5.4.1	Coherence Concepts in Optics.	170		
		5.4.2	Moving Diffusers and Coherence Reduction	172		
		5.4.3	Speckle Suppression by Reduction of Temporal Coherence	175		
		5.4.4	Speckle Suppression by Reduction of Spatial Coherence	178		
	5.5	Use of	Temporal Coherence to Destroy Spatial Coherence	185		
	5.6	Compo	ounding Speckle Suppression Techniques	186		
6	Spe	ckle in	Certain Imaging Applications	187		
2	-r-	Smaalel		107		
	6.1	Speckie	in Holossonku	10/		
	0.2	6 2 1	Dringinlag of Uplography	100		
		6.2.1	Speakla Suppression in Helegraphic Images	190		
	62	0.2.2 Smaalala	Speckie Suppression in Holographic images	192		
	0.3	Speckie	Our distance Tomography	195		
		6.3.1	Analysis of OCT	195		
		0.3.2	Analysis of UC1	196		
	<i>(</i>)	0.3.3	speckie and speckie suppression in OC1	200		
	6.4	Speckle	e in Optical Projection Displays	203		
		6.4.1	Anatomies of Projection Displays	204		
		6.4.2	Speckle Suppression in Projection Displays	208		

		6.4.3 Polarization Diversity	208
		6.4.4 A Moving Screen	209
		6.4.5 Wavelength Diversity	211
		6.4.6 Angle Diversity	211
		6.4.7 Overdesign of the Projection Optics	213
		6.4.8 Changing Diffuser Projected onto the Screen	214
		6.4.9 Specially Designed Screens	225
	6.5	Speckle in Projection Microlithography	228
		6.5.1 Coherence Properties of Excimer Lasers	228
		6.5.2 Temporal Speckle	229
		6.5.3 From Exposure Fluctuations to Line Position Fluctuations	231
7	Spe	ckle in Certain Nonimaging Applications	235
	7.1	Speckle in Multimode Fibers	235
	,	7.1.1 Modal Noise in Fibers	237
		7.1.2 Statistics of Constrained Speckle	239
		7.1.3 Frequency Dependence of Modal Noise	243
	7.2	Effects of Speckle on Optical Radar Performance	248
		7.2.1 Spatial Correlation of the Speckle Returned from Distant	
		Targets	250
		7.2.2 Speckle at Low Light Levels	252
		7.2.3 Detection Statistics—Direct Detection	256
		7.2.4 Detection Statistics—Heterodyne Detection	260
		7.2.5 Comparison of Direct Detection and Heterodyne Detection	270
		7.2.6 Reduction of the Effects of Speckle in Optical Radar	
		Detection	273
8	Spe	ckle and Metrology	275
	81	Speckle Photography	275
	0.1	8 1 1 In-Plane Displacement	277
		8.1.2 Simulation	279
		8.1.3 Properties of the Spectra $\mathcal{T}_{\mu}(v_{X}, v_{X})$	281
		8.1.4 Limitations on the Size of the Motion (x_0, v_0) .	284
		8.1.5 Analysis with Multiple Specklegram Windows	285
		816 Object Rotation	286
	8.2	Sneckle Interferometry	287
	0.2	8.2.1 Systems That Use Photographic Detection	287
		8.2.2 Flectronic Speckle Pattern Interferometry (ESPI)	291
		8.2.3 Speckle Shearing Interferometry	294
	83	From Fringe Patterns to Phase Maps	296
	0.5	8 3.1 The Fourier Transform Method	297
		8.3.2 Phase-Shifting Speckle Interferometry	298
		8.3.3 Phase Unwrapping	299

	8.4	Vibration Measurement Using Speckle	301	
	8.5	Speckle and Surface Roughness Measurements	305	
		8.5.1 RMS Surface Height and Surface Covariance Area from Speckle		
		Contrast	305	
		8.5.2 RMS Surface Height from Two-Wavelength Decorrelation	306	
		8.5.3 RMS Surface Height from Two-Angle Decorrelation	307	
		8.5.4 Information from Measurement of Angular Power Spectrum	308	
9	Speckle in Imaging Through the Atmosphere			
	9.1	Background	311	
		9.1.1 Refractive Index Fluctuations in the Atmosphere	311	
	9.2	Point-Spread Functions	313	
	9.3	Average Optical Transfer Functions	315	
	9.4	Statistical Properties of the Short-Exposure OTF and MTF	316	
	9.5	Astronomical Speckle Interferometry	322	
		9.5.1 Object Information that Is Retrievable	322	
		9.5.2 Results of a More Complete Analysis	325	
	9.6	The Cross-Spectrum or Knox–Thompson Technique	327	
		9.6.1 The Cross-Spectrum Transfer Function	327	
		9.6.2 Recovering Full Object Information from the Cross-Spectrum	329	
	9.7	The Bispectrum Technique	331	
		9.7.1 The Bispectrum Transfer Function	331	
		9.7.2 Recovering Full Object Information from the Bispectrum	332	
	9.8	Speckle Correlography	333	
A	Lin	ear Transformations of Speckle Fields	337	
В	Cor	ntrast of Partially Developed Speckle	341	
С	Stat	istics of Derivatives of Speckle	345	
Ū	~ .			
	C.I	The Correlation Matrix	345	
	C.2	Joint Density Function of the Derivatives of Phase	348	
	C.3	Joint Density Function of the Derivatives of Intensity	349	
D	Way	velength and Angle Dependence	351	
	D.1	Free-Space Geometry	351	
	D.2	Imaging Geometry	355	
Е	Spe	ckle Contrast with a Projected Diffuser	359	
	E.1	Random Phase Diffusers	359	
	E.2	Diffuser that Just Fills the Projection Optics.	362	
	E.3	Diffuser that Overfills the Projection Optics	362	

F	Statistics of Constrained Speckle	365	
G	Sample Mathematica Programs for Simulating Speckle		
	G.1 Speckle Simulation With Free Space Propagation	369	
	G.2 Speckle Simulation With an Imaging Geometry	369	
	Bibliography		
	Index	383	