Simulation method for non-Gaussian speckle in a partially coherent system

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Non-Gaussian speckle contrast from a phase-perturbed random object field in a spatially partially coherent system is simulated. A quasi-monochromatic extended incoherent source is modeled as a collection of independent point sources distributed on a regular grid. The source illuminates a phase screen object in a Kohler configuration. Speckle is calculated from the incoherent sum of irradiances in the image plane generated from the point sources. Simulated speckle contrasts are verified by an experiment with a fractallike rough surface distribution that is fabricated using a grayscale maskless lithography tool. Characteristics of the simulation method and physical quantities affecting speckle contrast are discussed. © 2009 Optical Society of America

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1. INTRODUCTION

Speckle is a common phenomenon in coherent optical systems. Understanding statistical characteristics of speckle is important for many applications. The relationship between a randomly phase-perturbed field generated by reflection or transmittance from a rough object and speckle has been of interest for several decades [1,2]. There are at least three factors affecting speckle statistics in optical imaging systems. One factor is object field statistics. For a phase-perturbed field generated by an object's rough surface, parameters statistically describing the rough surface affect speckle statistics. Another factor is the optical system. The shape and size of a system pupil and optical aberrations that are related to the coherent point spread function (PSF) of the system affect speckle [1,3]. A third factor is temporal or spatial coherence of the illumination. Speckle contrast is defined as

$$C_s = \sigma_I/\langle I \rangle, \tag{1}$$

where σ_I and $\langle I \rangle$ are standard deviation and mean of irradiances, respectively. It is well known that speckle contrast reduction occurs in a partially coherent optical system [4–7]. For example, root mean square (RMS) roughness of more than a wavelength generates fully developed speckle that has $C_s=1$. Speckle reduction by partially coherent illumination has been used to estimate roughness of a strong diffuser from speckle contrast. This paper introduces a simulation method for non-Gaussian speckle in a Kohler illumination system, where the simulation is verified from comparison with previously developed theories and experiment. Results indicate that aberration has a significant effect on non-Gaussian speckle contrast.

The fourth moment of the random image field can be calculated to evaluate speckle contrast on an image plane, where an eight-dimensional (8D) integration is required for 2D analysis. Even for a linear and shift-invariant system, a numerical calculation for speckle contrast using an 8D integration requires enormous computing power. Previously, speckle contrast from a rough surface illuminated by a partially coherent beam was numerically calculated based on the fourth moment of an image field, but that calculation was confined to a 1D case with a simplified coherent PSF and illumination mutual intensity to avoid heavy computation costs [4]. Calculating the fourth moment can be circumvented, if image field statistics are estimated according to statistics of the number N_s of independent scatters coherently contributing to the field at each observation point. When N_s is large, image field statistics are described by Gaussian functions because of the central limit theorem. This situation is physically equivalent to when the correlation length of the rough surface is much smaller than the effective width of the coherent PSF, and this situation is called Gaussian speckle.

There are many examples in the literature of non-Gaussian speckle, where N_s is small, but most of them concern scattering in nonimaging cases, such as far-field diffraction from a diffuse object [8–12]. Uozumi and Asakura showed qualitatively consistent results between experiment and theory from a random walk model for partially developed non-Gaussian speckle [13]. Jakeman and Pussy derived K-distribution statistics from a random walk model for a non-Gaussian field, where N_s obeys a negative binomial distribution with a sufficiently large $\bar{N}_s$ [14]. Barakat generalized the K-distribution for a weak scatterer [15]. Even though the K-distribution well describes non-Gaussian speckle in various scattering cases, relationships between physical and mathematical quantities have not been elucidated [16,17]. For nonimaging cases, N_s is estimated by comparing the area of an illumination beam with the correlation length on the rough object. However, for imaging cases, N_s is ambiguous, because the coherent PSF is not usually a well-bounded function, which makes directly applying random walk models in imaging cases difficult. Furthermore, it has

