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A new approach for determination of a mean speckle size in simulated speckle pattern

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ABSTRACT

In this paper one-dimensional correlation method for determination of a mean speckle size is used, while two various approaches are presented. It is shown, that accuracy of the measurement by the method depends on a number of speckles in an evaluated one-dimensional intensity profile of detected speckle pattern. It is also shown, that a significant optimization of the method by reduction of a number of intensity values representing detected speckle patterns can be performed. This study is carried out for several speckle patterns generated through a numerical simulation of the speckle fields after reflection of a Gaussian beam off a rough object's surface. Results of the determination of the mean speckle size are compared with theoretical predictions.

1. Introduction

Speckle effect occurs when a coherent light is either reflected from a rough surface or propagates through a medium having scattering centers randomly distributed [1]. In a detection plane we can observe a speckle pattern consisting of dark and bright speckles, distributed in a random way. The size of a speckle in the speckle pattern is a significant parameter, which can be exploited in metrology, e.g. for detection of the scattering centers concentration in a biological fluid [2], determination of the optical thickness [3] or measurement of an object's deformation [4]. Speckle size affects crucially the accuracy, sensitivity and range of measurement by various methods, such as speckle correlation method [5–7], digital speckle photography [8,9] or speckle interferometry [10]. Accuracy of measuring methods using so-called "dynamical speckles", which arise on moving objects, is also influenced by mean speckle size [11].

The aim of the paper is to show an appropriate way how to acquire the mean speckle size from the speckle pattern. In practice the mean speckle size is usually determined as a value where the vertical (horizontal) profile of the two-dimensional (2D) normalized autocorrelation function of intensity decreases to $1/e$ or $1/2$ [3]. Nevertheless, in this paper we study another, less conventional way to estimate the mean speckle size. This way involves computation of the one-dimensional (1D) normalized autocorrelation function of intensity as in [12] but a novel approach is proposed and is compared to the one used in [12].

The approach [12] (called an average 1D correlation method in this paper) is based on an algorithm proposed in [2]. Each vertical (horizontal) intensity profile of the speckle pattern is extracted as a series of values. For each profile the 1D normalized autocorrelation function of intensity is computed. The mean speckle size for the i-th profile (the profile speckle size) is defined as a value where

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the 1D normalized autocorrelation function decreases to $1/e$. An average of the profile speckle sizes is defined as the mean speckle size for the whole detected area. It has been shown, that the utilization of the larger area of the detector, which captures more speckles, positively influences the accuracy of the method. However, for smaller dimension of the detector is more convenient another approach of the speckle size determination, which is described below.

The novel approach (called a 1D correlation method of a long vector in this paper) is a novel way to the computation of mean speckle size by the 1D normalized autocorrelation function of intensity. Each vertical (horizontal) intensity profile of the speckle pattern is also extracted as a series of values, but these intensity profiles are subsequently concatenated into one row (column) vector. Then the 1D normalized autocorrelation function of intensity is computed only once for both horizontal and vertical directions. The mean speckle size for the resultant row (column) vector is defined as a value where the 1D normalized autocorrelation function of intensity decreases to $1/e$.

The advantage of the presented algorithms based on the computation of the 1D autocorrelation function of intensity is that they are faster than the conventional algorithm based on the computation of the 2D autocorrelation function of intensity [2,12]. Moreover, one can propose optimization of the determination of the mean speckle size by reduction of a number of intensity values representing the detected speckle pattern [12].

For simulation of the speckle effect the presented simulation model [13,14], which is based on direct computation of the Fresnel-Kirchhoff diffraction integral, is used. Within the numerical model the object generating the speckle effect is illuminated by a Gaussian beam propagating from its waist situated in front of the object. A beam radius in the object plane varies in consequence of controlled variation of a beam radius at the beam's waist. Then several speckle patterns with different speckle sizes are simulated, since the mean speckle size depends on the size of the beam spot in the object plane [1]. Two approaches for computation of the mean speckle size based on calculation of 1D correlation function of intensity (the average 1D correlation method and the 1D correlation method of a long vector) are applied. Numerical results of the determination of the mean speckle size for five different simulated speckle patterns for the Gaussian beam radii 30 μm, 40 μm, 50 μm, 60 μm and 70 μm, corresponding to speckle sizes within range (60–160) μm, are compared with results obtained from theoretical relations.

2. Theory

Fig. 1 shows the geometrical arrangement of the optical setup for detection of the speckle pattern used within the numerical simulation. The object's surface is placed in the object plane (x, y). Gaussian beam propagating from its waist of the radius ω_o situated at the distance L_s from the object plane (x, y) incidents on the object's surface forming a beam spot of a radius ω. Speckle pattern is detected in the detection plane (x', y') at the distance L_o from the object plane (x, y) and at the angle θ_o of observation.

The mean speckle size is defined as width of the normalized autocorrelation function r_I of intensity I of the speckle pattern observed in the detection plane (x', y'). For the 2D normalized autocorrelation function r_I of intensity I one can write [1–3]

$$r_I(\Delta x', \Delta y') = \frac{\langle I(x', y')I(x' - \Delta x', y' - \Delta y')\rangle - \langle I(x', y')\rangle^2}{\langle I(x', y')^2\rangle - \langle I(x', y')\rangle^2}. \quad (1)$$

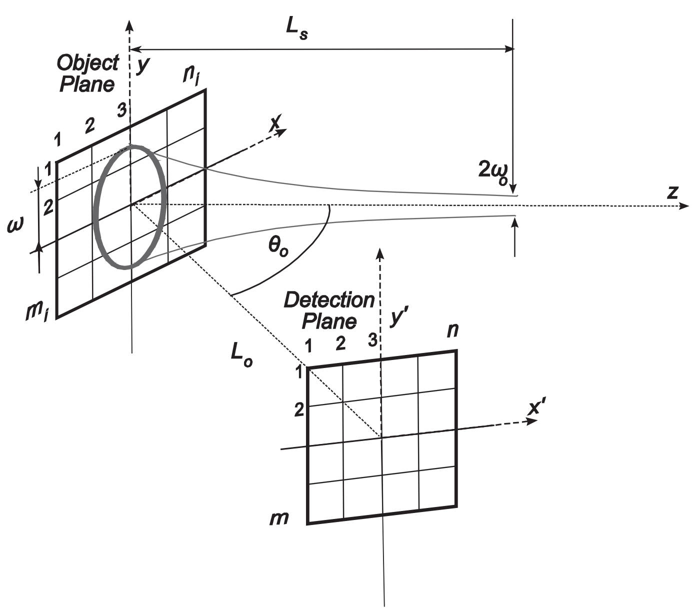

Fig. 1. The geometrical arrangement of the optical setup for detection of the speckle pattern used within the numerical simulation.