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Practical limits and opportunities with speckle metrology

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Abstract. In this presentation, the role of speckles as a carrier of information in phase-based optical metrology is re-visited. Starting with the fundamental mechanisms for speckle decorrelation it is shown that information about the state of an object is transferred through the modified mutual coherence function and can be detected either through the phase, speckle movement, speckle decorrelation or as a combination. The presentation is focusing on practical scale laws that set the limit for what is possible to achieve with present day technology and is demonstrated with a few examples incorporating measurements of microstructural changes, strain, shape, lenses and other refractive index objects.

1 Introduction

Applications in metrology were one of the original uses of the laser when introduced in the early 1960's. In particular the laser lay the foundation for the invention of holographic interferometry as a versatile tool for a great range of imaging measurement applications, nicely summarized by Vest [1]. Very quickly scientists noticed that holographic reconstructions always were accompanied by a grainy pattern called a speckle pattern and that this pattern limited the precision to which fringes could be located and resolved. However true, it was also realised that laser speckles carried unique information and that some properties of laser speckles could be used to enhance the performance of holographic interferometry as a metrology tool. This triggered scientists to investigate more deeply the origin and properties of laser speckles in all sorts of applications in optics, including metrology. The most complete summary is given by Goodman [2].

In this presentation, some basic properties that influence measurements utilizing laser speckles will be re-visited. It is shown that the precision of optical measurement systems in general can be understood from the correlation properties of laser speckles, both in a diffraction setting and in an imaging setting. It is further noted that image correlation in space and/or time gives information about the phase changes of the field that provides a route to perform interferometric measurements in disturbed environments. Examples will be shown how basic speckle properties can be used to calculate practical scaling laws for different types of measurements ranging from measurement of microstructural changes through measurements of strain, shape and refractive index to depth gated imaging. As such, the use of speckle theory in optical metrology stretches far beyond the original motivation to understand fringe formation in holographic interferometry. The rest of this paper is divided such that a few universal properties of laser speckles are sketched in section 2.1 followed by a discussion about limitations and possibilities with present day technology in section 2.2. The paper ends with a few examples from different areas of application.

2 Properties and tools

This section summarizes a few important speckle properties and tools used to extract useful information from time varying speckle fields.

2.1 Correlation properties

Consider the complex amplitudes $U_1(\mathbf{p_1}; \mathbf{X_1})$ and $U_2(\mathbf{p_2}; \mathbf{X_2})$, respectively, of a dynamic speckle field detected in a plane $\mathbf{X}$ and where the subscripts represent two different time instances. $\mathbf{p_1}$ and $\mathbf{p_2}$ are a list of parameters that specify a specific state of the measurement including object microstructure, illumination and detection directions, wavelength and geometry. The normalized correlation between the fields from these two instances may be expressed as [3],

$$\mu(\Delta\mathbf{X}) = \mu_\sigma(\Delta\mathbf{p}; \boldsymbol{\xi}) f(\Delta\mathbf{p}; \mathbf{x}) g(\Delta\mathbf{p}; \mathbf{X}), \qquad (1)$$

where $\Delta\mathbf{p}$ represents any change in the measurement state, $\boldsymbol{\xi}$ represents the speckle generating plane, $\mathbf{x}$ represents the aperture plane and $\mathbf{X}$ is the plane in which the measurement is performed. The correlation measured may hence be expressed as the product between three correlation functions associated with three distinct planes. The function $\mu_\sigma(\Delta\mathbf{p}; \boldsymbol{\xi})$ describes the effect of microscopic phase changes associated with the scattering volume of the object. For a pure surface scatter this function may often be ignored as it will always be close to unity, but for a volume scattering material it may change quickly even for very small changes in the state. For the two remaining correlation functions one needs to consider the macroscopic phase change $\phi(\Delta\mathbf{p}; \boldsymbol{\xi})$ associated with a change in state. The effect of this phase change is that the field will be rotated in space, which for moderate rotations may be approximated with a movement,

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$$\mathbf{u} = Lk^{-1}\nabla\phi, \qquad (2)$$

in the plane of interest; where L is a propagation length, k is the wavenumber and $\nabla\phi$ is the phase gradient. With this in mind, the function $f(\Delta\mathbf{p};\mathbf{x})$ may be expressed as $f(\mathbf{u}) = \int P(\mathbf{x}-\mathbf{u})P^{*}(\mathbf{x})d\mathbf{x}$, where $P(\mathbf{x})$ is the pupil function and * represents complex conjugation. In an imaging setting $P(\mathbf{x})$ is the entrance pupil and in the case of diffraction field detection it is in general the detector surface. The distance L is hence either the distance from the object surface to the entrance pupil plane or the distance between the object and the detector. The final correlation function, $g(\Delta\mathbf{p};\mathbf{X})$, represents the overlap between the speckles in the plane of evaluation. In an imaging setting, L becomes the distance between the object surface and the conjugate plane to the image. Hence, if the fields are evaluated in a plane in which the speckles remain stationary this correlation function can be ignored. This is however not true in general. The final correlation function, $\mu(\Delta\mathbf{X})$, has three parameters. The phase, ϕ, is the phase change associated with the change of state and is in general the parameter of primary interest. The displacement, $\mathbf{d} = \Delta\mathbf{X}_{max}$, given by the position of maximum correlation is related to the phase change through Eq. (2). Finally, the magnitude $|\mu|$ gives the precision with which ϕ and $\mathbf{d}$ may be determined. It may also be used to map areas with rapid changes in the microstructure.

2.2 Practical considerations

All measurements are limited by the hardware available and for measurements utilizing speckles often the limiting equipment is the detector. A general detector is characterized by its pixel pitch a, the number of pixels N (in both directions), and the sampling interval T. The importance of the pixel pitch is that it limits the numerical aperture at which a speckle field can be detected without aliasing. However, considering an object size S it may be shown that in practice all measurements utilizing speckles will be limited by the scaling law,

$$\nabla\phi < 2\pi\frac{N}{4S}, \qquad (3)$$

regardless of whether the imaging is performed with traditional imaging or a holographic reconstruction. As determined from the correlation function $f(\Delta\mathbf{p};\mathbf{x})$, the acceptable phase gradient over the object surface before total decorrelation occur is hence only limited by the size of the object in relation to the number of pixels on the detector. In addition, the dynamic microstructural phase change reducing the correlation parameter μ_σ will add another time-scale, which can be determined from calibration. Because of this there are two different detection modes in which speckle fields are detected. If the sampling interval, T, is sufficiently small, the changes can be resolved within the correlation time of the event and the phase changes can be detected directly. If the event is too rapid, the event is detected in a time average mode, which results in a loss of speckle contrast. In this mode direct access to the phase is not possible and the outcome is evaluated from a model relating speckle contrast with the parameter of interest.

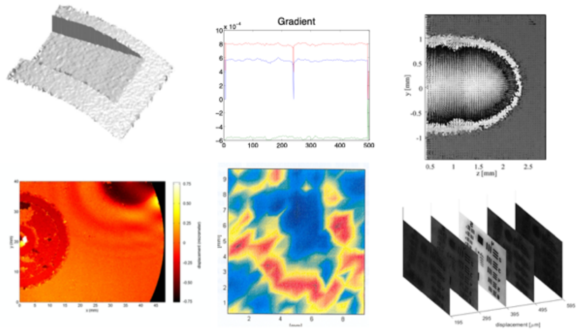

Fig. 1. Examples from various measurement results utilizing speckles.

3 Examples

A few examples from measurements utilizing speckles and the relations from section 2 are shown in Fig. 1. The top row shows examples in which Eq. (2) is used to robustify the calculation of the phase change. The top left image is an example from a dual-wavelength interferometry measurement of shape [4]. The middle image shows a measurement of uniaxial strain with symmetrical dual wavelength illumination [5], and the right image shows a measurement of an explosion using interferometric speckle deflectometry [6]. In the bottom row the left image shows the measurement of a transient wave on a rotating hard disc, in which the bulk rotation is withdrawn based on an image correlation calculation [7]. The middle image shows a measurement of microstructural activity in a sheet of copy paper and the right image shows an example of depth gated imaging utilizing the three-dimensional size of a rapidly changing speckle pattern as a spatial gate [8].

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