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Decorrelation noise due to surface shape in two-wavelength holographic imaging

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Abstract: This paper presents a model for decorrelation noise due to surface shape in two-wavelength digital holography. Theory is supported by numerical simulations giving very good agreement. © 2021 The Author(s)

1. Introduction

The use of two-wavelengths in holographic imaging have been shown to be a relevant tool for surface roughness and shape measurements [1–3]. With a unique wavelength, the measured surface height of any natural object (non polished) is ambiguous if larger than the wavelength. Since the surface of the object also includes roughness, then the surface shape cannot be reconstructed because the phase extracted from the digital holograms results from a speckle pattern. The ambiguity and randomness of this phase can be mitigated with the use of another wavelength leading to the synthetic wavelength. It follows that the unambiguous range becomes increased from microns to millimeter or larger. Considering two wavelengths λ_1 and λ_2 , the synthetic wavelength is given by $\Lambda = \lambda_1 \lambda_2 / |\lambda_1 - \lambda_2|$ [4]. However, there is an inherent issue of using several wavelengths that is related to the speckle decorrelation arising when the primary illumination wavelength is changed to extend to the next one. This induces a phase noise in the phase difference calculated from the two phases at the two wavelengths. The decorrelation noise is related to both the surface roughness and shape. This paper proposes a novel result for the theoretical modelling to describe the speckle noise decorrelation in phase data from two-wavelength holographic imaging.

2. Theory

The complex-valued field O emerging from the holographic system is related to the initial object field A by the convolution equation $O(\mathbf{X}) = PSF(\mathbf{X}) * A(\mathbf{X})$, with $PSF(\mathbf{X})$ being the point spread function of the holographic imaging system. In the case of surface shape measurement with multi-wavelength digital holography, the surface is illuminated with different wavelengths. Since the surface is rough, the image field is a speckle pattern and its phase is uniformly distributed over the interval $[-\pi, +\pi]$. Especially, phase differences between different wavelengths are of interest. Those phase differences exhibit speckle decorrelation noise that is due to the natural decorrelation from the wavelength change and that from the surface shape. The characterization of the speckle decorrelation can be investigated by considering the complex coherence factor of the speckle fields [4]. The complex coherence factor is a scaled version of the mutual intensity between two fields O_1 and O_2 obtained for two different wavelengths λ_1 and λ_2 at the output of the holographic system, such as [4]:

$$\mu = \frac{\langle O_1(\mathbf{X}_1, \lambda_1) O_2^*(\mathbf{X}_2, \lambda_2) \rangle}{\sqrt{\langle |O_1(\mathbf{X}_1, \lambda_1)|^2 \rangle \langle |O_2(\mathbf{X}_1, \lambda_1)|^2 \rangle}}, \quad (1)$$

where $\langle \dots \rangle$ stands for ensemble average and $*$ for complex conjugate. Calculation of Eq. (1) is not straightforward, but in this paper we provide the expression of the modulus of $|\mu|$, valid for $\sqrt{\alpha_x^2 + \alpha_y^2} / \Lambda \leq 4R_u$ (0 if not) and for normal illumination and observation of the surface:

$$|\mu| = \frac{2}{\pi} \exp \left[-\frac{8\pi^2 S_q^2}{\Lambda^2} \right] \left(\cos^{-1} \left(\frac{1}{\Lambda R_u} \sqrt{\alpha_x^2 + \alpha_y^2} \right) - \frac{1}{\Lambda R_u} \sqrt{\alpha_x^2 + \alpha_y^2} \times \sqrt{1 - \frac{1}{\Lambda^2 R_u^2} (\alpha_x^2 + \alpha_y^2)} \right), \quad (2)$$

where α_x, α_y are the local surface slopes of the object shape, S_q is the standard deviation of the surface roughness, and R_u is the cut-off frequency of the holographic system.

3. Simulation

A realistic simulation is carried out to produce phase maps from two-wavelength digital holography with corruption by speckle decorrelation noise. The surface shape with the given topography and roughness is supposed to be illuminated by wavelengths in the visible range of light. The aperture diaphragm of the imaging system is adjusted to control the size of the speckle grain in the image plane and to simulate realistic phase images. The cutoff frequency is then related to the number of pixels per speckle gain N_s and we have $R_u = 0.61/(N_s p_x)$ [5], where p_x is the pixel pitch of the sensor. In order to generate speckle fields at two different wavelengths, optical fields are successively computed for λ_1 and λ_2 keeping constant the topography and surface roughness [5].

4. Results

The initial wavelength is chosen at $\lambda_1 = 0.6328 \mu\text{m}$ and $\Delta\lambda = |\lambda_2 - \lambda_1| = 2 \text{ nm}$ so that $\Lambda = 200.9 \mu\text{m}$. The number of pixels per grain is set to $N_s = 4$ and $N_s = 8$ and $p_x = 5 \mu\text{m}$. For roughness, the value $S_q = 10\lambda_1$ and two spatial correlation lengths $\rho_r = p_x$ and $\rho_r = 5p_x$ are considered (ρ_r is the correlation length of the roughness). A continuous surface with total height almost at $2000 \mu\text{m}$ is considered and shown in Fig. 1(a). A large number of phase fringes is generated in order to get a large variety of slopes as given in Fig. 1(b). The decorrelation noise is estimated and shown in Fig. 1(c). From Eq. (2), the speckle noise decorrelation can be estimated by considering the surface shape topography and the roughness. The local slopes were estimated over 16×16 patches along the surface. In addition the decorrelation noise in the patches was estimated to provide $|\mu|$. Thus 256 values of the surface slope and $|\mu|$ are obtained and plotted in Fig. 1(d). As can be seen for the different parameters N_s , S_q , ρ_r , the experimental data points from the simulations fit very well the theoretical prediction. Note that the surface slopes are represented as spatial frequencies $u_0 = \sqrt{\alpha_x^2 + \alpha_y^2}/\Lambda$, that is the surface slope related to the synthetic wavelength.

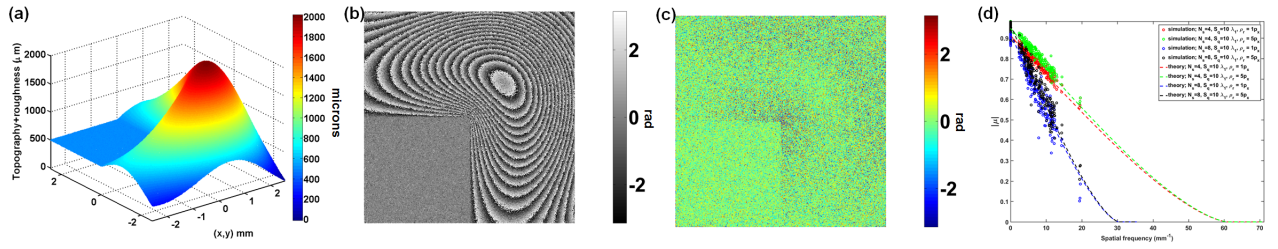


Fig. 1. (a) surface topography and roughness, (b) noisy modulo 2π phase fringe pattern obtained with $\Lambda = 200.85 \mu\text{m}$, (c) map of the speckle decorrelation phase noise, (d) $|\mu|$ vs slope represented as spatial frequencies for cases $N_s = (4, 8)$, $S_q = 10\lambda_1$, $\rho_r = (1p_x, 5p_x)$; dashed lines: Eq. (2).

5. Conclusion

This paper proposes a novel expression of the modulus of the coherence factor in the case of two-wavelength holographic imaging in order to estimate the speckle decorrelation phase noise in surface shape measurements. The results demonstrate the very good agreement between the theory and the realistic simulations. This opens the way for a predictive noise analysis in order to better adapt the de-noising strategies in the data processing in multi-wavelength digital holography.

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