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Single-shot interferogram analysis for accurate reconstruction of step phase objects

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We describe a constrained optimization approach for demodulation of single-shot interferograms corresponding to step phase objects. The demodulation problem is formulated as a minimization problem for a cost function consisting of a L2-norm squared error term and a gradient-based penalty (total variation) suitable for step objects. The optimization approach is tested with two methods that use complex (or Wirtinger) derivatives for the iterative solution update. The first simplistic method has a free parameter and thus provides a family of solutions. The second method is practically more valuable in that it is adaptive in nature and automatically leads to an appropriate solution. Both the off-axis case with straight line fringes and the on-axis case with closed fringes are treated in a unified manner. Excellent recovery of the phase of the step object suggests that the optimization approach as presented here is capable of providing full detector resolution, which is usually difficult to achieve in single-shot interferogram analysis.

OCIS codes: (100.3175) Interferometric imaging; (100.3010) Image reconstruction techniques; (100.2650) Fringe analysis; (100.3190) Inverse problems.

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1. INTRODUCTION

Interferometric phase measurement is one of the most commonly used techniques in optics and has multiple routine applications, such as surface metrology [1], biomedical imaging [2], and digital holographic imaging [3]. With the availability of sensitive digital array sensors (CCD/CMOS), it is now possible to record a high-contrast interference data frame with a short exposure time (submillisecond range) with nominal illumination conditions, so that most ambient vibrations have no detrimental effect on the single-frame record. The possibility of demodulating the single-shot interference pattern with full detector resolution can be attractive from the perspective of system simplicity and cost in most practical interferometry applications. Such a system can, for example, find applications in the optical metrology of step objects and image plane digital holographic microscopy, where it is desirable to retain information about the sharp edges in the object to be imaged. In this paper, our focus is to present a method for demodulation of single-shot interferograms corresponding to step objects. While we study this specific problem here, the proposed methods can be readily extended to a variety of interferometric imaging problems as we will report in the future.

An interference pattern recorded on a 2D detector array may be modeled as

$$H = |R|^2 + |O|^2 + R^* O + R O^*. \tag{1}$$

Here H is the interference intensity record, R is the reference beam, which we assume to be known, and O is the unknown complex-valued object function to be determined. Furthermore, H, R, and O are two-dimensional functions of the (x, y) coordinates corresponding to the locations of the pixels in an array sensor. At present, there are two most commonly used approaches to interferogram analysis in the literature: the phase shifting method (PSM) [4] and the Fourier transform method (FTM) [5,6]. PSM can achieve full detector resolution, however, it requires three or more interference data frames with predetermined phase shifts introduced in the reference beam. FTM, on the other hand, is a single-shot method and relies on the Fourier structure of an off-axis interferogram. If the dc and cross terms in the 2D Fourier transform of the interferogram are well separated, the interferogram may be demodulated by filtering out the desired cross term. For illustration, consider a circular phase object with a phase step equal to $2\pi/3$, as shown in Fig. 1(a). An off-axis interferogram intensity pattern obtained by interfering the complex waves corresponding to the step phase object and a tilted plane wave is shown in Fig. 1(b). The images are 500×500 pixels in dimension. The step object is centered in the image frame and has a radius of 100 pixels. The reference beam is assumed to be of the form $R = \exp[i2\pi(f_x x + f_y y)]$. Here the (x, y) pixel size is 1 unit and the values of the spatial frequencies have been selected as $f_x = f_y = 0.04$ pixel^{-1} for this illustration. Furthermore, the