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Accurate efficient carrier estimation for single-shot digital holographic imaging

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Off-axis digital holograms are commonly processed using the Fourier transform method. This method requires estimation of the carrier frequency peak in the two-dimensional Fourier domain. The accuracy of peak location information using the standard fast Fourier transform (FFT) routines is limited by the pixel size, thus giving rise to a residual carrier component in the reconstructed image. In this Letter, we use an efficient two-step process for cross-term peak location to sub-pixel accuracy where the standard FFT-based peak finding procedure is followed by a high-resolution discrete Fourier transform (DFT) calculation at the nominal peak location. It is shown that the residual tilt artifacts due to a small change in the magnitude of the carrier frequency or due to the rotation of the fringe pattern are uniformly removed with this method. For a digital hologram of size $M \times N$ pixels, the high-resolution DFT calculation with an up-sampling factor of α requires an additional computational effort of $O(MN\alpha)$ which is marginal when $\alpha \ll M, N$ and, thus, provides a practical single-shot method for accurate demodulation of digital holograms.

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Interferometric/holographic imaging is an important technique in optics that finds several applications such as digital holographic microscopy [1,2], surface metrology [3], optical coherence tomography [4], and astronomical imaging [5]. Ready availability of digital sensor arrays (CCD/CMOS) and computational power have made it possible to achieve fast practical interferometric systems that enable quantitative phase imaging. The object information in a hologram is typically encoded in the form of fringe modulation. Therefore, fringe demodulation is a central problem of interest in the processing of digitally recorded interference patterns. Off-axis holography configuration [6] remains a popular choice among the interferometric systems due to its ability to separate the dc and cross-terms in the recorded hologram in Fourier space. This leads to a straightforward image reconstruction process known as the Fourier transform method (FTM) [7,8]. Consider a digitally recorded off-axis hologram H represented as

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

Here R and O represent the reference and object beams respectively. All the variables H, R, and O above are two-dimensional (2D) functions of the pixel co-ordinates (x, y) of the detector array used for recording H. We will assume that the reference beam is of the form $R = \exp[i2\pi(f_{x0}x + f_{y0}y)]$, corresponding to a tilted plane wave. The 2D Fourier transform of the hologram thus consists of a dc peak corresponding to the intensity terms in Eq. (1) and two cross-term peaks. When using FTM, the carrier fringe frequency (f_{x0}, f_{y0}) is first determined from the 2D Fourier transform of the function $H(x, y)$ computed using the readily available fast Fourier transform (FFT) routines. A region of Fourier space surrounding this cross-term peak is then filtered out and shifted to zero frequency location. Finally, an inverse Fourier transform operation leads to the object reconstruction. Accurate knowledge of the reference beam phase is also required for other fringe demodulation techniques such as the phase shifting method [3] and the more recent optimization techniques [9,10]. Quantitative reconstruction of $O(x, y)$, therefore, critically depends on the determination of the carrier frequency peak location in the Fourier domain.

For an interference pattern of size $M \times N$ pixels, the FFT routines typically calculate the Fourier transform of the same size and, as a result, the location of the cross-term peak is limited by the pixel size. In a typical hologram recording, the carrier fringe peak is usually located at a sub-pixel location, and not using this sub-pixel information can lead to residual phase error in the reconstructed image as we illustrate next. Consider a hologram simulated using a quadratic phase function $O = \exp[i\beta(x^2 + y^2)]$, as shown in Fig. 1(a), and a tilted plane wave reference beam given by $R = \exp[i2\pi(f_{x0}x + f_{y0}y)]$. Here the (x, y) coordinates range from $(-250, 249)$ with unit pixel size. The other parameters used are $\beta = 10^{-5}$ and $f_{x0} = f_{y0} = 0.04$ pixel^{-1}. The resultant hologram, the corresponding FTM processing, and the phase reconstruction are shown in Figs. 1(b), 1(d), and 1(f), respectively. The red circle in Fig. 1(d) represents the Fourier domain filter used for reconstruction purposes. The radius of this circle is selected to be 0.7 times the distance between the dc and the cross-term peaks. The phase error map between Figs 1(a) and 1(f) is shown