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Optimising electron holography in the presence of partial coherence and instrument instabilities

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ABSTRACT

Off-axis electron holography provides a direct means of retrieving the phase of the wavefield in a transmission electron microscope, enabling measurement of electric and magnetic fields at length scales from microns to nanometers. To maximise the accuracy of the technique, it is important to acquire holograms using experimental conditions that optimise the phase resolution for a given spatial resolution. These conditions are determined by a number of competing parameters, especially the spatial coherence and the instrument instabilities. Here, we describe a simple, yet accurate, model for predicting the dose rate and exposure time that give the best phase resolution in a single hologram. Experimental studies were undertaken to verify the model of spatial coherence and instrument instabilities that are required for the optimisation. The model is applicable to electron holography in both standard mode and Lorentz mode, and it is relatively simple to apply.

1. Introduction

Off-axis holography in the transmission electron microscope (TEM) is an established technique for measuring the electrostatic and magnetic properties of materials and devices. The technique reconstructs the phase shifts experienced by the electron wavefield and uses them to map the spatially varying electric or magnetic field. In the pursuit of measuring the increasingly weaker electric and magnetic fields generated from nanomaterials, the necessary improvements in the resolution of the reconstructed phase have been pursued using various strategies, which can be loosely categorised according to instrumental improvements, and improvements in data acquisition and processing.

There exists a fairly extensive body of literature reporting phase resolution improvements within both of the above-mentioned categories. In general, the phase resolution can be improved only by increasing the *coherent* electron dose. On the instrumentation side, higher coherent doses have been achieved by brighter electron sources [1,2] and the use of elliptical illumination [3,4]. Improvements in microscope stability enable larger doses via longer exposure times [5]. The improvement of a charge-coupled device (CCD) camera's modulation transfer function (MTF) can also increase the detectable coherent dose [6]. On the data acquisition and processing side, a greater dose and hence better phase resolution has been achieved by the use of multiple holograms [7–9], which applies also to the case of phase-shifting holography [10–12].

Considering the number of available methods for improving the phase resolution, it is important to understand the dominant factors that limit the phase resolution. Typically, many of the experimental parameters are pre-determined by the requirements of the specimen. These include the hologram fringe spacing (which determines the spatial resolution), overlap width (which determines the field of view), and magnification (which should be as high as the overlap width allows). These parameters are therefore regarded as essentially fixed. The remaining parameters with which we can optimise phase resolution can be grouped into two categories, namely the partial spatial coherence and the instrument instabilities. These parameters are controlled via the electron dose and exposure time, respectively.

In this paper, we describe a simple, yet accurate, model capable of predicting the dose rate and exposure time that give the best phase resolution in a single hologram. To make the presentation tractable, we have restricted our attention to the instrumental factors affecting holography, and have not concerned ourselves explicitly with factors associated with the specimen. Hence our results reflect the best-possible phase resolution that can be achieved under given conditions on a particular instrument. In the presence of specimen drift and/or dose-dependent specimen damage, the optimum dose rate given here remains entirely valid, while the

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optimum exposure time may need to be reduced accordingly.

In light of the considerable body of literature describing the theories and experimental factors governing the phase resolution in off-axis electron holography [4,7,13–17], our work requires some justification: our aim is to provide a simple and practical methodology, as free as possible of unnecessary details. In particular, the models for spatial coherence and instrument instabilities are kept as simple as possible. Furthermore, we describe a minimal experimental dataset that can be used to predict the optimum conditions for all combinations of fringe spacings, overlap widths and magnifications. Our results can also be applied, with minimal modification, to the case where multiple holograms are used.

This paper is organised as follows: Section 2 provides some background on the concept of a phase error in electron holography. In Section 3 we outline the theoretical model used for predicting the optimum conditions. Section 4 describes our experimental setup and processing methods. Our results and discussion are presented in Section 5. In Section 6 we discuss the extension to elliptical illumination before concluding in Section 7.

2. The phase error

The phase resolution, herein referred to as the phase *error*, determines the minimum difference that can be distinguished in the reconstructed phase (here we are concerned with statistical errors rather than systematic ones). Fig. 1(a) illustrates the phase error associated with an arbitrary point in the reconstructed wave function. In the ideal case, each point of the wave function would correspond to a point in the Argand plane. However, due to the finite electron dose (among other reasons), there is always a statistical error associated with the complex value ψ. In Fig. 1(a) this error is represented as a cluster of points spread symmetrically around the nominal value ψ, the points corresponding to the values obtained by repeated independent measurements. The phase error is typically defined as the standard deviation $\Delta\phi$ of the repeated phase measurements [13–15].

For the case illustrated in Fig. 1(a), the phase error is given to good approximation by $\Delta\phi \approx \Delta\psi/A_{mean}$. For very low doses, however, the noise in the reconstructed phase grows to the extent that the phase error represented by this simple formula becomes ill-defined (in extreme cases the phase error so calculated will exceed 2π). This problem can be remedied by using the standard deviation associated with the cosine and sine of the phase, as illustrated in Fig. 1(b). The latter definition has the benefit of remaining well defined for arbitrarily low doses. The two definitions are equivalent for sufficiently high doses.

3. Theory

The interference pattern produced by two partially coherent plane waves $e^{2\pi i\mathbf{k}_1\cdot\mathbf{x}}/\sqrt{2}$ and $e^{2\pi i\mathbf{k}_2\cdot\mathbf{x}}/\sqrt{2}$, as measured by a pixelated electron detector in an off-axis holographic setup, is described by the expression

$$N(\mathbf{x}) = CN_e\left[1 + \frac{V}{2}e^{2\pi i\mathbf{k}_1\cdot\mathbf{x}}e^{-2\pi i\mathbf{k}_2\cdot\mathbf{x}} + \frac{V^*}{2}e^{-2\pi i\mathbf{k}_1\cdot\mathbf{x}}e^{2\pi i\mathbf{k}_2\cdot\mathbf{x}}\right] = CN_e\left[1 + |V|\cos(2\pi(\mathbf{k}_1 - \mathbf{k}_2)\cdot\mathbf{x} + \arg V)\right]. \quad (1)$$

This expression describes a set of cosinusoidal fringes sitting on a constant background, expressed in terms of detector signal $N(\mathbf{x})$, where N_e is the average number of detected electrons per pixel, C is a constant which we describe below, the complex number V weights the interference terms and obeys $0 \le |V| \le 1$, and $\arg V$ denotes the complex argument (or phase) of V. The number V incorporates any factors that lead to a damping of the interference fringes in a relative sense, which include the partial spatial coherence of the beam, instabilities of the instrument, and the less-than-perfect modulation transfer function (MTF) of the detector. The magnitude $|V|$ is the visibility of the interference fringes (also termed the fringe contrast). The constant C equals the average signal output from the detector per incident electron, and so it incorporates factors such as the less-than-perfect detector quantum efficiency (DQE) and the detector gain G.

3.1. Phase error and the effective signal

Following Fourier processing of the off-axis hologram, the statistical phase error in a given pixel in the reconstructed wave function is given approximately by the expression

$$\Delta\phi \approx \left(\frac{2G}{N_{\text{eff}}}\right)^{1/2}, \quad (2)$$

where N_{eff} is the *effective* signal per pixel [13,14]. The latter is defined as

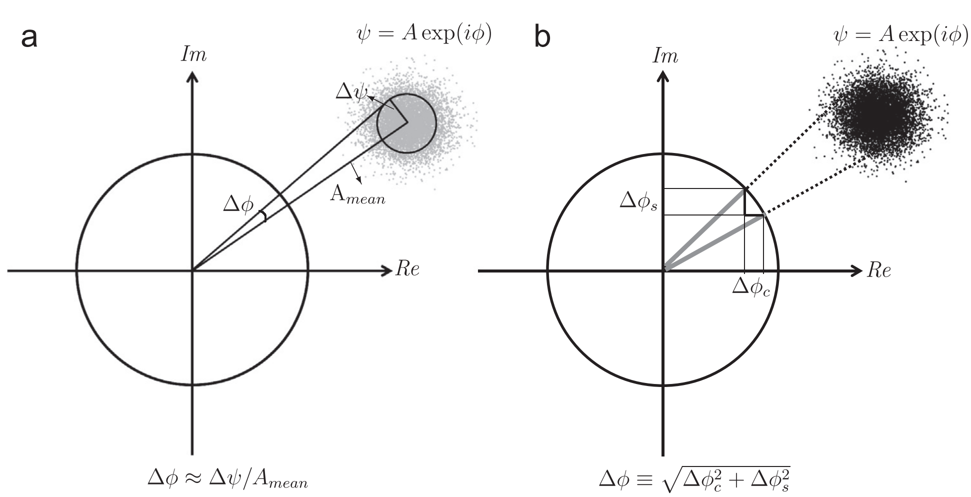

Fig. 1. Schematic representations of the phase error associated with a given point in the reconstructed wave function ψ. (a) Conventional definition of the phase error, applicable when the dose level is sufficiently high. (b) Definition of the phase error in terms of the cosine and sine of the phase. The definition in (b) remains well-defined for arbitrarily low doses. For high doses these definitions become equivalent.