Analytical Phase-Shifting Electron Holography using Fresnel-corrected holograms

Augustin Nogier[1], Aurélien Masseboeuf[1], Kévin Garello[1]
[1]SPINTEC, Grenoble, France

Background incl. aims
Unlike conventional Transmission Electron Microscopy (TEM) techniques, Electron Holography (EH) gives an access to the phase of the electron wave, which makes it suited for imaging electromagnetic fields with fine sensitivity and a spatial resolution in the range of nanometers [1].

When performing a measurement, the complex wave contribution of the sample is contained in the object band of the Fourier transform of the recorded hologram. For this reason, the most common way of extracting the sample phase contribution consists in applying a circular mask around the object band [2]. This low-pass filtering cuts off excessive noise and undesirable Fresnel diffraction effects, but also limits the final spatial resolution of the recovered phase map. While this limit may not be an issue depending on the scale of interest, such a loss of precision can lead to artefacts in the phase maps realignment process when working with finer details, which remains a critical step in separating the electric and magnetic contributions.

Other approaches overcome this by combining two holograms to suppress the zero-order band [3], effectively doubling the maximum mask size available and typically getting the spatial resolution down to 2 - 3 nm. This may not be enough in some cases though. A solution to this problem is the Phase Shifting (PS) method, which uses linear combinations of a greater amount of holograms to mathematically isolate the object band [4], thus negating the necessity to apply a mask in Fourier space and allowing for a theoretical pixel precision.

Implementations tend to use specific initial phase values in order to get back to an ideal diagonal matrix system, which greatly facilitates the calculation. When working with arbitrary initial phase values, it is still possible to avoid the complex matrix inversion by performing sine fittings in each pixel, using an even greater amount of hologram recordings [5]. Due to the absence of any filtering however, Fresnel modulation effects become a source of errors in the reconstruction process in both cases. However, this effect can be rendered ineffective by adjusting the hologram fringes spacing to match that of the modulation pattern [5].

In this work, we aim for the pixel-precise reconstruction of phase maps using a modification of the PS method, so that the recovered sharp atomic details can lead to better phase maps alignments. This study focuses primarily on a more general analytical solution to the PS equation in the case of arbitrary chosen initial phase values, which eliminates the need to conform to an ideal case. We also investigate the use of biprism voltage as a suitable way to minimize Fresnel modulation effects and related calculation errors. Finally, we apply these methods to both computer simulations and TEM measurements from specifically prepared magnetic samples.

Methods

The general analytic solution we derived to the PS matrix equation works for any set of non-redundant initial phases containing at least three elements. While more measurements ultimately yield less noise in the final phase map, we typically used 5 or 7 hologram recordings for each manipulation up to this point. As common as it is for this matter, we used beam tilting to tune each initial phase value. Under the small angle approximation and disregarding the Fresnel modulation pattern, this is equivalent to an overall phase offset in the fringe pattern. The experimental values can then be extracted for each hologram from the center of the object band in Fourier space and be used as parameters in the solution expression.

Since there is no requirement regarding the fringe spacing in the holograms, we also choose to tune the biprism voltage low enough to give a sufficiently good contrast while still cancelling out the Fresnel effect. Up to this point, all of our measurements have used this particular setting.

Results

Our computer simulations use artificially generated phase and amplitude maps from which holograms are calculated. We first tested our method on square-shaped phase maps with various apodizations, noise levels and Fresnel diffraction effects. Using our analytical method on Fresnel-free holograms, we see that the reconstructed phase maps show accurate reconstructions of the initial wavefront regardless of the spatial details [Fig.1].
Additionally, we measured the Fresnel modulation effect on holograms for various biprism voltage values in order to minimize this effect. So far, all of our experimental results have thus been using a voltage of 21 V instead of the usual 200V, which corresponds to 24nm-wide fringes for an image pixel resolution of 0.12 nm.

Conclusions

We were able to reconstruct phase maps using our generalized PS analytical method for reasonable noise and Fresnel modulation levels. While this method works best on perfectly generated holograms, we also have shown that it is possible to maximize the fringe contrast and correct the Fresnel modulation effect by adjusting the biprism voltage. Likewise, other

parameters such as the initial phase do not need to match ideal values since our method takes the experimental measurements into account.
Using this modified phase shifting method, we expect that further testing done on specifically prepared samples can give satisfactory results with an effective spatial resolution approaching the theoretical pixel size.

Graphic:

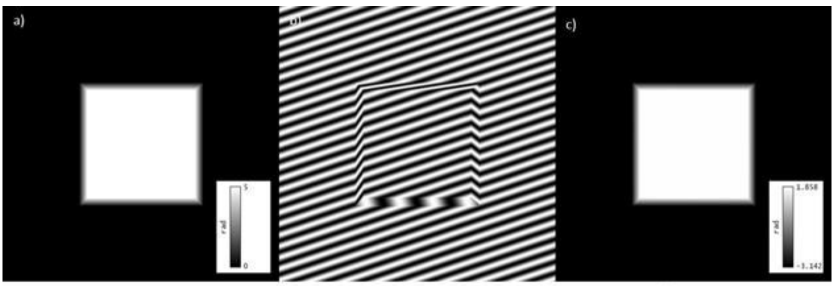

Fig.1 : Simulation result of the phase shifting process: a) Artificially generated phase map; b) One of the 7 simulated holograms with arbitrary initial phases; c) Recovered final phase map

Keywords:

Holography, phase-shifting, biprism, Fresnel, modulation

Reference:

[1] Martha R. McCartney, Rafal E. Dunin-Borkowski, David J. Smith: Quantitative measurement of nanoscale electrostatic potentials and charges using off-axis electron holography: Developments and opportunities, Ultramicroscopy 203 (2019) 105–118
[2] Qi Fan, Hongru Yang, Gaoping Li and Jianlin Zhao: Suppressing carrier removal error in the Fourier transform method for interferogram analysis, J. Opt. 12 115401 (2010)
[3] V.V. Volkov, M.G.Han, Y.Zhu: Double-resolution electron holography with simple Fourier transform of fringe-shifted holograms, Ultramicroscopy134 (2013) 175–184
[4] Q. Ru, G. Lai, K. Aoyama, J. Endo, A. Tonomura: Principle and application of phase-shifting electron holography, Ultramicroscopy 55 (1994) 209-220
[5] Kazuo Yamamoto, Yoshihiro Sugawara, Martha R. McCartney and David J. Smith: Phase-shifting electron holography for atomic image reconstruction, Journal of Electron Microscopy 59 S81–S88 (2010)