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Dynamical Holographic Moirés in a TEM

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Abstract

A new electron interferometry method has been developed and implemented in a transmission electron microscope to quantitatively analyse magnetic and electric properties emanating from objects using holograms free of artifacts and with a frequential sensitivity. This method, called Dynamical Holographic Moirés (DHM), is based on the double-exposure technique consisting in the superimposition of two different holograms. We improved this technique by acquiring the superimposed holograms for two well-defined excitation states of the sample and with a control of the superimposition frequency. The variations of magnetic and electrostatic fields between both excitation states can then be extracted directly from the amplitude part of the so-called interferogram. We demonstrate the efficiency of this method by studying quantitatively the magnetic field generated by a Hard Disk Drive writing head excited by a DC and an AC current. Double exposure measurements have also been performed to study *in situ* electrostatic properties of a biased carbon nanocone tip. Our method opens the route to dynamical studies using the unique combination of nanoscale resolution

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and electromagnetic sensitivity of electron interferometry.

Keywords: transmission electron microscopy, electron holography, phase reconstruction, electromagnetic fields, Holographic Moirés

1. Introduction

Off-axis Electron Holography (EH) [1] is a powerful interferometric method carried out in Transmission Electron Microscopy (TEM) which enables to recover the phase shift that the fast electron beam experiences when interacting with any electrostatic and/or magnetic field. This interaction between the incident electron beam and the electromagnetic field is described by the Aharonov-Bohm effect (AB) [2] using the following expression :

$$\begin{aligned}\phi(\mathbf{r}) &= C_E \int_{\infty} V(\mathbf{r}, z) dz - \frac{e}{\hbar} \int_{\infty} A_z(\mathbf{r}, z) dz \\ &= C_E \int_{\infty} V(\mathbf{r}, z) dz - \frac{\pi}{\Phi_0} \int \int_{\infty} B_{\perp}(\mathbf{r}, z) dr dz\end{aligned}$$

where :

$\mathbf{r}$ and z are the 2D vector in the object/conjugated planes and the coordinates along the optical axis respectively

C_E is an electron wavelength related constant

V is the electrostatic potential

ϕ_0 is the magnetic flux quantum equal to $\frac{h}{2e}$ where e and h are respectively the elementary charge and the Planck constant. $\phi_0 \approx 2.06810^{-15} Wb$.

A_z is the component of the magnetic potential vector parallel to the electron beam and is thus linked to magnetic induction gradients in the image

17 plane.

18 $B_{\perp}$ is the component of the magnetic induction perpendicular to both r and

19 z .

20 Since the AB effect was experimentally been demonstrated using off-axis EH
21 by Tonomura [1], electron interferometry was used as an efficient tool for the
22 quantitative mapping of electrostatic and magnetic fields appearing within and
23 around a sample with a nanometer spatial resolution [3, 4, 5, 6, 7, 8, 9, 10].
24 EH has also been proved to be sensitive to the atomic displacement (and so the
25 strain fields) by studying the phase shift between diffracted beams through the
26 Dark-Field Electron Holography technique [11, 12] which is partially described
27 as a Moirés method. A Moirés pattern consists on interference fringes resulting
28 of the superimposition of two spatial periodic structures. As a result, a modu-
29 lation of the image intensity appears within the pattern. A simple distinction
30 between Moirés pattern and EH can be draw by the part of the wave under
31 interest : Moirés fringes appear as changes in the amplitude of the exit electron
32 wave while EH aims at retrieving the full exit wave, mostly focusing on its phase
33 part.

34 Moirés method has intensively been used in TEM for decades for the study of
35 lattices deformation : stacking faults [13], crystal orientation [14], dislocations
36 [15], graphene stacks misalignments [16, 17, 18], thickness estimation [19] are
37 some of the structural properties that can been studied using Moirés patterns.
38 More recently Moirés method has been implemented in high resolution STEM
39 [20] : the STEM Moirés fringes for a regularly periodic lattice arise when the

40 interval of pixels defined by the scanning step is close to a lattice spacing of
41 crystalline or to a multiple of it.

42 The technique described in this paper combines Electron Holography and Moirés
43 patterns to improve the field sensitivity achievable in TEM through a frequency
44 study and to develop the so-called Dynamical Holographic Moirés (DHM) me-
45 thod. The basic idea of DHM is to superimpose two holograms obtained on a
46 same area of an object which is periodically stated in two different but control-
47 led configurations (either electrostatic or magnetic). The overlapping of both
48 holograms gives rise to Moirés contrasts in the final amplitude image carried
49 out by the fringes of the holograms.

50 This idea already proposed in optical interferometry is based on the so-called
51 double exposure technique (or holographic interferometry) and was formerly
52 used in a photonic bench. As examples of application, it enabled to access va-
53 riations of gas distribution during an arc discharge or to the macroscopic de-
54 formation of a given objects under external stress [21, 22]. It was then firstly
55 implemented in a electron microscope 30 years ago [23] and applied to off-axis
56 EH experiments on electromagnetic fields [24, 25, 26].

57 The double exposure technique presents different advantages. First at all
58 the signal can be directly visualized and interpreted from the obtained image
59 by observing the modulation of the amplitude of fringes. Secondly it is not
60 necessary to correct the DHM pattern for any perturbations of the reference
61 wave (as it has to be done for EH) as these perturbations do not contribute
62 to the modulated amplitude if they remain the same for both holograms which

63 will be overlapped. Finally the Moirés contrasts linked to the relative signal
 64 between both holograms are not influenced by the distortions originating from
 65 the microscope setup (projector lens, camera,...) as they remain identical for all
 66 images recorded at the same magnification. These advantages explain why the
 67 use of such a technique was initially mandatory for simply and quantitatively
 68 mapping electromagnetic information at a large scale of pure phase objects.
 69 An exhaustive and complete review of this technique can be found in ref [27].
 70 Double exposure EH has been further developed by various groups to improve
 71 the phase sensitivity by implementing various wavefront tilting [28, 29] or inter-
 72 fering waves number [30, 31].
 73 However, the main drawback of this method is a lower spatial resolution and a
 74 lower sensitivity to weak signals compared to the ones obtained in off-axis EH.
 75 In addition, the superimposition between both holograms requires to necessary
 76 record the holograms with identical conditions and to control the signal change
 77 between them. In addition, the emergence of computational hologram treatment
 78 as well as the great improvement of CCD cameras with high pixels density, fast
 79 acquisition rate and high pixel dynamic turned out this technique less used
 80 with respect to achievable modern methods (Fast Fourier treatment) which are
 81 less time consuming for an improved sensitivity. Nevertheless, browsing the nu-
 82 merous techniques commonly used in industrial interferometric holography, it
 83 appears that the double exposure method is somehow the preliminary step to-
 84 wards dynamical characterization tools like the so-called *real time* and *time*
 85 *average* holographic interferometry [32].

86

87 The purpose of this paper is to show the implementation of the time-average
 88 holographic interferometry in a TEM using the combination of off-axis EH and
 89 *in situ* techniques. We highlight in the following the DHM capabilities with
 90 two different *in situ* EH experiments : the first concerns the measurement of
 91 magnetic induction generated by a writer pole of a Hard Disk Drive (HDD) as a
 92 function of the AC current sent into its coils and the second is the electrostatic
 93 field emanating from a biased carbon nanotube studied *in situ* by EH.

94 2. Methods

95 The DHM method is depicted by an illustration using the calculated elec-
 96 trostatic field from a virtual charged sphere. Let us consider that the charge
 97 state of such a sphere can be modulated between a positive and negative state.
 98 The only feature required in our experiment is to be able to switch the charge
 99 state of the sphere without any other modification of the optical system du-
 100 ring the acquisition time. We define two coherent electron waves $\psi_{l,r}(\mathbf{r}, s) =$
 101 $A_{l,r}(\mathbf{r}, s)\exp(i\phi_{l,r}(\mathbf{r}, s))$ passing on the left (*l*) and the right (*r*) side of a Möl-
 102 lenstedt biprism which can be overlapped by applying a suitable voltage on
 103 the biprism. *s* corresponds only to the object contribution to the phase (e.g.
 104 the charge of the virtual sphere). The resulting interference pattern (i.e. the
 105 hologram) contains the phase difference between the two beams $\Delta\phi(\mathbf{r}, s) =$
 106 $\phi_{l,s}(\mathbf{r}, s) - \phi_{r,s}(\mathbf{r}, s)$ but also the phase distortions coming from the microscope
 107 setup $\phi_{\mu}(\mathbf{r})$. Fig. 1.b presents $\Delta\phi(\mathbf{r}, s) + \phi_{\mu}(\mathbf{r}, s)$ for a simulated positive charge

FIGURE 1: a) Phase image simulation of a sphere with a positive charge of $100\ e$ (field of view equal to $1\ \mu\text{m}$). b) Phase image simulation of the same sphere including experimental phase distortions due to the microscope setup (projector lens and CCD camera). c) and d) Simulated holograms for a positive and negative charge respectively. e) Double exposure hologram (interferogram) corresponding to the addition of the two previous hologram. f) Electrostatic map obtained from the amplitude analysis of the interferogram in (f).

108 where we added the experimental phase distortions from a microscope setup
 109 (projector lens of Hitachi HF3300C and Gatan US1000 CCD camera).
 110 The intensity of corresponding hologram with spatial wave vector $\mathbf{k}_0$ (Fig.
 111 1.c) can be written as :

$$I_H(\mathbf{r}, s) = |A_l(\mathbf{r}, s)|^2 + |A_r(\mathbf{r}, s)|^2 + 2A_l(\mathbf{r}, s)A_r(\mathbf{r}, s)\cos(\mathbf{k}_0 \cdot \mathbf{r} + \Delta\phi(\mathbf{r}, s) + \phi_\mu(\mathbf{r})) \quad (1)$$

This hologram displays a fringe deformation coming from the electric field generated by the sphere. The phase difference between the two beams $\Delta\phi(\mathbf{r}, s)$ is usually extracted by Fourier filtering while the phase distortions $\phi_\mu(\mathbf{r})$ are removed recording a reference hologram in the vacuum or knowing the different contributions to the phase distortions (projector lens, CCD camera,...) [33]. The Fig. 1.d shows the same hologram for an opposite charge.

The recorded image using the double exposure method corresponds to a simple addition of the half intensity of both previous holograms where s_1 and s_2 describe two different charge states (here opposite states with $s_1 = -s_2$) :

$$\begin{aligned} I_{DHM}(\mathbf{r}) &= \frac{1}{2} (I_H(\mathbf{r}, s_1) + I_H(\mathbf{r}, s_2)) \\ &= |A_l(\mathbf{r}, s_1)|^2 + |A_r(\mathbf{r}, s_2)|^2 + A_l(\mathbf{r}, s_1)A_r(\mathbf{r}, s_2) (\cos(\mathbf{k}_0 \cdot \mathbf{r} + \Delta\phi(\mathbf{r}, s_1) + \phi_\mu(\mathbf{r}))) \\ &\quad + \cos(\mathbf{k}_0 \cdot \mathbf{r} + \Delta\phi(\mathbf{r}, s_2)) + \phi_\mu(\mathbf{r})) \end{aligned}$$

which can be rewritten into

$$I_{DHM}(\mathbf{r}) = |A_l(\mathbf{r}, s_1)|^2 + |A_r(\mathbf{r}, s_2)|^2 + 2A_l(\mathbf{r}, s_1)A_r(\mathbf{r}, s_2) \cos\left(\frac{\Delta\phi(\mathbf{r}, s_1) - \Delta\phi(\mathbf{r}, s_2)}{2}\right) \cos\left(\mathbf{k}_0 \cdot \mathbf{r} + \frac{\Delta\phi(\mathbf{r}, s_1) + \Delta\phi(\mathbf{r}, s_2)}{2} + \phi_\mu(\mathbf{r})\right),$$

112

113 This simple mathematical description shows that the amplitude of the holo-
 114 graphic fringes is modulated by the cosine of the phase difference $\Delta\phi(\mathbf{r}, s_1) -$
 115 $\Delta\phi(\mathbf{r}, s_2)$ between both superimposed states. This associated cosine term //
 116 $|\cos\left(\frac{\Delta\phi(\mathbf{r}, s_1) - \Delta\phi(\mathbf{r}, s_2)}{2}\right)|$ then corresponds to the envelop function of these ho-
 117 lographic fringes and is the origin of the Moirés contrasts. Note that this term
 118 does not depend on the holographic fringe periodicity *i.e.* the applied voltage
 119 on the biprism. As depicted Fig. 1.a and Fig. 1.e, we can clearly observe the
 120 appearance of the Moirés pattern which can be emphasized by the use of a clas-
 121 sical Fourier filtering on the fringe frequency (Fig. 1.f). This double exposure
 122 hologram will be hereafter designed as an *interferogram* and is the core of the
 123 DHM technique.

124 It is straightforward to observe that the shape of the Moirés pattern within
 125 the interferogram only represents the variation of the electrostatic potential
 126 (equal to twice the electric field) emanating from the charged sphere, while the
 127 phase distortions due to the microscope optic and the camera have been remo-
 128 ved. As a consequence, the interferogram contains a quantitative information
 129 on the relative variation of the magnetic and/or electric potential between two
 130 defined states without any contribution from any other phase terms remaining
 131 constant during such variation. The distance between two maxima (white lines)
 132 or two minima (black lines) corresponds to a difference of one period of the
 133 holographic fringes between both superimposed holograms, *i.e.* a phase shift of
 134 2π coming from the presence of an electromagnetic field. For example, in case

135 of magnetic induction only (no changes in the electrostatic contribution), it
 136 delimits a magnetic flux equal to $2\Phi_0$. For an electric field, this distance repre-
 137 sents a variation of the projected electrostatic potential (*i.e.* integrated along
 138 the electron path) of $\frac{2\pi}{C_E}$. The experimental challenge to perform successfully
 139 such DHM experiment relies on the ability to quickly vary and control the elec-
 140 tromagnetic field for making an addition of at least two defined states during
 141 the acquisition time, keeping the whole optical alignment stable without any
 142 change. Microelectronic devices whose state can be tuned in two configurations
 143 by an external alternative input of various frequencies are perfect systems to be
 144 studied by DHM . Any defined state can then be studied with any frequency.

145

146 3. Results and discussion

147 The major assumption made in the DHM description is the possibility to
 148 change and to control the magnetic or the electric state only of the sample
 149 under study. In a previous EH experiment we have successfully studied the ma-
 150 gnetic field emanating from a Hard Disk Drive (HDD) writer pole [34]. In this
 151 previous paper, we developed a novel strategy that allows *in situ* imaging an
 152 operational write pole of a HDD slider in a TEM in normal working conditions.
 153 The complete local hysteresis loop on each point of a large area has been obtai-
 154 ned while the magnetic signals originating only from the write pole and those of
 155 the shield material have been separated and quantitatively analyzed changing
 156 the applied current through the write coils. The writing/erasing magnetic field

FIGURE 2: Off-axis electron holography performed on a HDD writing head reported in [34].
a and b) Wrapped magnetic phase images obtained for a current injected of $+60\text{ mA}$ and -60 mA respectively. c and d) Half sum and half difference of the phase images displayed in a and b revealing respectively the pole and shield contributions

157 is generated by the current flowing in the coils intended to behave linearly with
 158 the applied current without hysteresis when reversing the current to allow for
 159 a fast and accurate writing and erasing of data. To precisely tailor the profile
 160 of emanating magnetic field, the current carrying coils and bulk magnetic ma-
 161 terial of the writer are shielded from the disk media. This also insures that the
 162 magnetic environment experienced by the media is dominated by the write pole
 163 and not from other surfaces of this three dimensional electromagnetic device.
 164 These shields are composed of soft magnetic materials to amplify the magnetic
 165 field gradients coming out of the write pole (more details on the HDD writer
 166 part description in ref [34]). The slider was carefully prepared to be electrically
 167 bounded on a dedicated TEM sample holder. We achieved to make a thin TEM
 168 sample reducing the overall size of a HDD slider from 1.2 mm down to 30 μm
 169 by mechanically polishing while keeping intact the writer coils and the electrical
 170 contact pads. The *in situ* EH experiment was performed in Lorentz mode on
 171 a Cs-corrected Tecnai F20 microscope operating at 200kV. The Möllenstedt bi-
 172 prism, positioned parallel to the surface of the slider at a distance of about 600
 173 nm, is used to create the interference pattern (applied voltage of 140V giving
 174 a fringes periodicity equal to 2nm). The resulting electron hologram then allows
 175 extraction of the phase shift between the electron beam interacting with the
 176 generated magnetic induction field in front of the write pole and a reference
 177 beam that passes far from it through an almost field-free region [34]. In this
 178 experiment, the electron phase shift is only related to the magnetic induction
 179 through the Aharanov-Bohm relation presented in the first part of this article

180 as no electrostatic signal is present.

181 It is then possible to inject either a positive (Fig. 2.a) or a negative (Fig. 2.b)
182 DC current through the coil of the pole during EH experiment for phase analysis.
183 The white rectangle on the middle left side is the write pole location. Stating
184 that the magnetic flux generated is symmetric with respect to the current sign,
185 simple half sum (Fig. 2.c) and half subtraction (Fig. 2.d) of two phase images
186 obtained for opposite currents were performed to access to the intrinsic writer
187 pole magnetic flux and the intrinsic magnetic shield contribution respectively.
188 Using a complete set of excitation currents between -60 mA and $+60\text{ mA}$, we
189 are able to obtain a hysteresis loop along any direction of the magnetic flux
190 being emitted by the pole and the shield for any location in the studied area.
191 More details regarding this experiment as the influence of the weak signal in the
192 reference wave can be found in [34]. Fig. 3.a presents the hysteresis loops of the
193 horizontal component (*i.e.* perpendicular direction to the surface of the pole) of
194 the projected magnetic inductions for the pole and the shield. They have been
195 calculated from an area located in front of the write pole at a distance of 5 nm
196 from its surface as marked by the orange square on the Fig. 2.c and Fig. 2.d.
197 We can clearly observe that the shield contribution presents a rather constant
198 and low value while the pole contribution shows an important variation of the
199 projected magnetic induction. The highest value corresponding to the magnetic
200 saturation of the projected induction at 118 T.nm is reached for an applied
201 current around 20 mA . Finally Fig. 3.a demonstrates the absence of remnant
202 and coercive fields that are both expected for a HDD read/write device.

FIGURE 3: Time-Averaged holographic interferometry on the HDD writing head. a) Hysteresis loop of the horizontal magnetic induction component (perpendicular to the pole surface) for the writing pole (black) and the shield (red). Colored dots and corresponding $\Delta\phi_i$ correspond to the amplitude signal between the excitation states used in the following interferograms. b)

203 When an AC square current is sent into the coils (instead a DC one), the
 204 emanating magnetic field oscillates between the two states defined by the AC
 205 square signal. The oscillation of the signal may then be tuned with different
 206 current values and frequencies during the acquisition time allowing to obtain
 207 interferograms by the DHM method. The amplitude part of these interfero-
 208 grams displayed in Fig. 3 corresponds to the ones obtained for the AC signal
 209 depicted with a color code on the hysteresis loop. The frequency was set at 1
 210 kHz and the acquisition time at 4 s meaning that 4000 holograms were overlap-
 211 ped (2000 for each current value/magnetic state). We start our description with
 212 the case of an AC square signal between -60 and $+60\text{ mA}$ @ 1 kHz which are
 213 the maximal values of injected current. The corresponding magnetic variation is
 214 represented on Fig. 3.a by $\Delta\phi_c$. The resulting interferogram directly recorded
 215 by the CCD camera is displayed Fig. 3.b. From the extracted amplitude image
 216 by Fourier analysis with a circular numerical mask giving a spatial resolution
 217 of 6 nm (Fig. 3.c), we clearly see that the Moirés pattern fits qualitatively with
 218 the intrinsic signal of the pole only as depicted in Fig. 2.c. This illustrates that
 219 the shield contribution, which remains constant (as well as any constant phase
 220 distortion coming from the microscope setup), is not contributing to the DHM
 221 amplitude and that DHM only reveals the magnetic changes associated to the
 222 AC square current. Approximately 10 white lines surrounded by dark lines ema-
 223 nating from the writer part can be deducted. They then correspond roughly to
 224 a total magnetic flux of $20\phi_0$ *i.e.* 41.3610^{-15} Wb
 225 If the AC signal is set between -60 and 0 mA ($\Delta\phi_d$), the amplitude of the ma-

226 gnetic variation of the pole contribution is the half of the previous one. We do
 227 observe on the corresponding image (Fig. 3.d) only 5 white lines from the writer
 228 pole giving a total magnetic flux of $10\phi_0$ which is also the half of the previous
 229 signal. With a AC signal set between 20 and 60 mA ($\Delta\phi_d$), the two states are
 230 in the same saturated part of the hysteresis loop. As a consequence, no magne-
 231 tic variation arose and the amplitude image of the corresponding interferogram
 232 shows a uniform contrast although a large magnetic induction is generated in
 233 front of the writer pole. This result confirms the sensitivity of DHM only to the
 234 magnetic variation between both different states.

235 A more detailed analysis on the quantification of the magnetic flux is presented
 236 Fig. 4.a : on this graph are given the profiles extracted along the white arrow
 237 in Fig. 3.c for the magnetic variations corresponding to $\Delta\phi_e$ (-60 to $+60 mA$
 238 in red), $\Delta\phi_d$ (-60 to $0 mA$ in blue) and $\Delta\phi_e$ ($+20$ to $+60 mA$ in yellow). As
 239 detailed previously, the distance between two minima (dark lines on the am-
 240 plitude image) corresponds to a phase shift of 2π between both superimposed
 241 holograms. This phase shift is equivalent to a magnetic flux variation of $2\Phi_0$
 242 ($4.13610^{-15} Wb$) through a surface perpendicular to the induction defined by a
 243 rectangle with a width equal to the distance between minima and an infinite
 244 length parallel to the electron beam. Dividing this flux by the distance between
 245 minima amounts to obtain the integrated magnetic induction along the electron
 246 path (unit T.nm) which is the physical parameter reported in the hysteresis
 247 loop presented Fig. 3.a. From the red curve in Fig. 4.a, the distance between
 248 two minima (centered on the writer pole) is measured to be about 18 nm gi-

249 ving a projected induction variation of 230 T.nm. This variation corresponds to
 250 twice the saturated magnetic induction ($\Delta\phi_d$ for -60 to $+60$ mA) : we have
 251 to divide by 2 to obtain the final value of the saturated induction equal to 115
 252 T.nm. This value is very close to the one measured by classical off-axis EH and
 253 reported on the hysteresis loop. Using the blue curve with $\Delta\phi_d$ as variation, the
 254 distance between two minima is now 36 nm which is twice the previous distance.
 255 The corresponding projected induction is then half of the previous one and so
 256 in agreement with the value obtained by off-axis EH. The yellow curve ($\Delta\phi_e$)
 257 confirms the absence of real magnetic variation between the two states even in
 258 the presence of an important magnetic field.

259 If we now probe the signal within the hysteresis loop, keeping a constant AC
 260 current amplitude of 20 mA, *i.e.* between -10 and 10 mA ($\Delta\phi_f$) and between
 261 -15 and 5 mA ($\Delta\phi_g$), we define the same magnetic variation than $\Delta\phi_d$ since
 262 the magnetic saturation is almost achieved for an applied current of 20 mA. On
 263 the corresponding amplitudes images Fig. 3.f and Fig. 3.g, the same quantifica-
 264 tion of the emitted magnetic flux is obtained : 5 whites lines for a total magnetic
 265 flux of $10\Phi_0$. The Fig. 4.b shows the nice superimposition of the corresponding
 266 quantitative profiles and illustrates the same variation of the projected magne-
 267 tic induction at various levels equal to 115 T.nm. Some slight differences can
 268 however be noticed between the two amplitude images in Fig. 3.f and Fig. 3.g
 269 and the one between -60 and 0 mA in Fig. 3.d. These discrepancies are also
 270 visible at the extremities of the profiles. They can be explained studying which
 271 parts of the hysteresis loop contribute to the DHM pattern : the first two cases

272 ($\Delta\phi_f$) and $\Delta\phi_g$) are located on the linear variation of the magnetic flux with
 273 the injected current while the last one includes the saturated part. Even if the
 274 saturation state is reached, small variations in the magnetic flux can arise with
 275 the overflow current and certainly the interaction between the fields produced
 276 by the pole and the magnetic shield is different. Both effects may induce the
 277 asymmetry while keeping valid the quantification of the magnetic flux that is
 278 measured at the vicinity of the pole.

279 As a brief summary of these results, we claim that DHM allows to probe
 280 all part of the hysteresis loop independently, without any complex data treat-
 281 ment and in a qualitative way. In addition, the magnetic response of this device
 282 under the application of an alternative current can be studied for different AC
 283 frequencies. DHM allows then to study the frequency dependence of the system
 284 under consideration, as described below.

285

286 The behaviour of the HDD writer head is now studied as a function of fre-
 287 quency with a fixed amplitude signal (-60 and 60 mA). The frequency is tuned
 288 from 0.5 Hz to 50 kHz keeping the acquisition time fixed to 4 s . Two variations
 289 can thus be expected in that case : first at all the signal quality could be mod-
 290 fied with the frequency as more holograms are added in a single interferogram
 291 and secondly inductance effect could arise when increasing the frequency thus
 292 modulating the magnetic flux. Four different interferograms for four different
 293 frequencies are depicted in Fig. 5. : no noticeable modification of the magnetic
 294 flux spreading from the pole is observed : the shape shown on the amplitude

FIGURE 4: Profiles of interferograms extracted from Fig. 3.a at a distance of 5 nm from the surface (white arrow of Fig. 3.c). a) Profiles extracted from Fig. 3.c, d and e). b) Profiles extracted from Fig. 3.d, f and g).

FIGURE 5: Frequency analysis on the interferograms at a fixed amplitude of $+/- 60 \text{ mA}$. a - d) Frequency of 1 Hz , 100 Hz , 10 kHz and 50 kHz respectively. e) Profiles of interferogram (same as in Fig. 4. extracted from various frequency measurements).

FIGURE 6: Double exposure holography on a field emitting Carbon Cone nanoTip. a) Raw hologram obtained for the emitting CCnT during its collapse. b) Amplitude extracted from a).

295 images (Fig. 5.a to Fig. 5.d) as well as the value of the projected induction
 296 deduced from profiles in Fig. 5.e remain the same. We observed only an impor-
 297 tant decrease of the fringe amplitude close to the write pole for ‘high-frequency’
 298 excitations ($\geq 10kHz$). This is supposed to be related to our experimental set
 299 up (sample holder, source meter and cables) that is not designed for such high
 300 frequency experiments producing possible decay of the electrical power and me-
 301 chanical vibrations. As it worth noting that a standard HDD writing head is
 302 supposed to work at a frequency of $2.4GHz$, a dedicated sample holder for high
 303 frequency signals should be used to explore such high frequency domain in order
 304 to observe and study local dumping due to the inductance effect.

305 We performed a last experiment on the HDD writer head changing the ap-
 306 plied voltage on the biprism (*i.e.* the distance between the holographic fringes)
 307 keeping the others parameters constant. As expected no effect of the biprism
 308 voltage is observed : the periodicity of the holographic fringes does not interfere

309 with the formation of the Moiré pattern.

310 The Fig. 6.illustrates the capability of DHM in the observation of other types
311 of signal using other kind of stimuli. In a previous work we studied *in situ* the
312 field emission process of Carbon Cone nanoTips (CCnT) [35]. During a parti-
313 cular Electron Holography experiment it turned out that the CCnT broke due
314 to an arc discharge during the acquisition time of an hologram. The analyze of
315 the amplitude of the resulting hologram (Fig. 6.a) evidences a nice pattern cor-
316 responding to the electrostatic potential changes when the tip is switched down
317 from +100 V to 0 V (Fig. 6.b). On the contrary to the HHD writing head analy-
318 sis previously described and for which time-average holographic interferometry
319 was performed, that unintentional DHM experiment carried out on the CCnT
320 is a simple double exposure experiment. Nevertheless it clearly evidences the
321 performances of DHM experiments to study devices in which the electrostatic
322 field can be switched between two states. It is however obvious that high AC
323 electric field application in a TEM is a more complex task as it deviates easily
324 the electron beam and is tedious to master particularly within the objective
325 pole pieces of a TEM.

326

327 This last remark is in fact a general drawback of the DHM method : it
328 requires to master the combined complexity of both the EH and *in situ* expe-
329 rimental constraints. Moreover DHM is only limited to the study of perfectly
330 reversible processes for which the two states that are superimposed in the inter-
331 ferogram are fully reproducible. Finally the quantification of the interferogram

332 is realized with a lower spatial resolution compared to the phase image obtained
 333 by off-axis EH. In addition, the appearance of the Moiré pattern is linked to a
 334 sufficient variation of the signal allowing multiple of 2π phase shift. This method
 335 is therefore not adapted to the study of weak signal variations. However DHM
 336 method offers a very interesting alternative to off-axis EH in some cases. The
 337 main drawback of traditional off-axis EH experiments is that the electron wave
 338 not only experiences phase shifts due to its interaction with the electromagnetic
 339 field of the object under consideration (and the surrounding stray fields) but
 340 also with the microscope setup (including the microscope lenses and the CCD
 341 camera distortions). Therefore, the requested phase information is always mixed
 342 with unexpected phase modulation arising from the microscope setup. These ar-
 343 tifacts can be removed using a couple of holograms [36]. A second limitation of
 344 off-axis EH may occur when no reference area of the studied field of view on the
 345 phase image can be chosen to correct the slope arising from the Fourier ana-
 346 lysis (misalignment between the center of the numerical mask and the carrier
 347 frequency). This problem can be encountered when studying a magnetic wall
 348 and its leak field. The third limitation is that, like most of the TEM methods,
 349 typical acquisition time for EH experiment is between hundred of milliseconds
 350 to ten seconds, limiting the technique to pseudo-static studies. Dynamical stu-
 351 dies in TEM require the use of complex instruments ([37, 38]) where electron
 352 pulses are generated by photo-emission processes thanks to the use of control-
 353 led pulsed laser. Up to now the limited brightness and poor spatial coherence of
 354 the ultrafast photocathodes used in these advanced Dynamical-TEMs (DTEMs)

355 does not permit to perform electron interferometry experiments on them. We
356 claim that our new DHM method is addressing (at least part of) all these three
357 points. We showed that phase distortions either coming from the microscope
358 setup are not influencing DHM interferograms. Moreover DHM interferograms
359 can be directly quantified without any needs of other image treatments. They
360 can be obtained between different defined excitation states and used to study
361 the resulting signal variation in terms of amplitude and distribution. Most of
362 all, the possibility to tune the frequency opens the way to emphasis dynamical
363 effects and damping functions such as inductance or capacitance (at the expand
364 of instrumental developments toward high frequency signal injection).

365

366 **Conclusion**

367 We showed that this DHM technique raised the possibility of studying easily
368 and quantitatively a system that is stated in two reproducible magnetic or
369 electrostatic configurations and to extract quantitative information on these
370 configurations without time consuming and complex electron hologram analysis.
371 This technique was demonstrated to overcome traditional EH limitations such
372 as artifacts from the microscope setup or others static constant phase shift
373 contributions. We succeed in analyzing dynamically the behavior of a HDD
374 writing head and studying different part of the corresponding hysteresis loop.
375 Similar analysis could be implemented to study electric fields.

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