Reduction of phase artifacts in differential phase contrast computed tomography

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Abstract: X-ray differential phase contrast computed tomography (DPC CT) with a Talbot-Lau interferometer setup allows visualizing the three-dimensional distribution of the refractive index by measuring the shifts of an interference pattern due to phase variations of the X-ray beam. Unfortunately, severe reconstruction artifacts appear in the presence of differential phase wrapping and clipping. In this paper, we propose to use the attenuation contrast, which is obtained from the same measurement, for correcting the DPC signal. Using the example of a DPC CT measurement with pronounced phase artifacts, we will discuss the efficiency of our phase artifact correction method.

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1. Introduction

X-ray computed tomography (CT) allows determining the three-dimensional shape of an object [1] and is a valuable tool in medicine, life science and nondestructive testing. Conventional CT is based on measuring the attenuation of X-rays in a test object. However, attenuation contrast (henceforth referred as AC) imaging has some disadvantages, e.g. the absorbed radiation dose is high and light materials become transparent at high X-ray energies [2,3]. A high absorbed radiation dose is objectionable in medical applications and the huge variation of the attenuation among different materials renders nondestructive testing of objects composed of light and dense materials difficult [1]. Indeed, the difference in attenuation between light and dense materials can easily reach 5 orders of magnitude [2,3]. Therefore, an X-ray beam has to cover a much longer distance in a light material than in a dense one in order to induce a detectable change of its intensity. On the contrary, a considerable phase shift of X-rays is induced even by light materials at high energies [2,3], which allows minimizing the radiation dose and visualizing regions of low density within a highly absorbing sample. Therefore, X-ray phase contrast imaging attracted a lot of interest in medicine and life science, and lately also in material science [4–9]. Recently, it was shown that a Talbot-Lau interferometer setup [10] enables differential phase contrast (DPC) imaging with low brilliance sources [7]. This discovery will possibly spread the use of phase contrast imaging in science and nondestructive testing.

A Talbot-Lau interferometer generates a periodic interference pattern which can be approximated by a sinusoidal curve [10,11]. The mean value of the interference pattern, in the ideal case, corresponds to the line integral of the attenuation coefficient along the X-ray beam. The ratio of the amplitude by the mean is a measure of the scattering, and the shift of the interference modulation is proportional to the derivative of the line integral over the real part of the refractive index [12]. If the attenuation, dark field and DPC images are measured at different angles, a three-dimensional image of the respective values can be calculated. However, the results of real measurements can deviate substantially from the ideal value of the line integral, causing reconstruction artifacts. So-called beam-hardening artifacts in AC tomography are well-known and methods for their correction are established [1]. However, they fail to correct artifacts in DPC tomography which are caused by differential phase wrapping and clipping. In this paper, we propose and demonstrate a method to reduce these artifacts.

2. Phase artifact correction

Erroneous values in the DPC projections will cause artifacts in the reconstructed 3D phase image. The 3D phase image is reconstructed from the DPC projections by integrating the 2D differential phase image. If incorrect differential phase values are located on the integration path the resulting phase values will be inaccurate. Conventionally, the differential phase is solely measured in one dimension, which reduces the measurement time by half and which avoids the need of either rotating one-dimensional grids during the measurement or using two-dimensional grids. In these cases, the integration path is unique and erroneous DPC values can't be bypassed.

One source of error causing incorrect differential phase values is missing or incorrect unwrapping of the differential phase. Conventional phase unwrapping methods require that the sampled signal is not aliased, i.e. that local phase differences are smaller than $\pi$ [13]. However, DPC measurements frequently don't comply with this requirement, and therefore these methods can’t be applied. Another source of error is differential phase clipping which occurs whenever the differential phase changes within one pixel.

The phase artifact correction presented in this paper remediates both sources of error, differential phase wrapping and clipping. It is based on the observation that the AC and DPC images are not independent of each other. Therefore, the AC image can assist to correct the DPC image at the places where differential phase wrapping or clipping occurs. The advantage of this approach is that no a priori information or assumptions about the geometry of the test
object are required. The procedure is based on the measurement of the AC image, on information about the materials of the sample and on parameters of the measurement setup. It also works with DPC images where the differential phase is solely measured in one dimension. Finally, the proposed correction method performs well even for under-sampled DPC images, i.e. in situations of aliasing.

The propagation of X-ray in matter can be described with a complex refractive index as in conventional optics \[2,3\]:

\[
n = 1 - \delta - i\beta = 1 - \frac{r_0}{2\pi} \sum_{q} n_q f_q (0, E),
\]

where \(\delta\) is the decrement of the real part of the complex refraction index and \(\beta\) is the complex part, \(r_0\) is the classical radius of an electron, \(\lambda\) is the wavelength, \(n_q\) is the number of atoms of type \(q\) per unit volume and \(f_q(0, E)\) is the complex forward atomic scattering factor for atom \(q\). The real and complex part of \(f_q\) are a function of the atomic photoabsorption cross section \(\mu_a(E)\) and related to each other by a modified Kramers-Kronig relation \[2,3\].

In our experiment, the mean value, the shift and the amplitude of the interference pattern created by a Talbot-Lau interferometer are measured by a phase stepping procedure \[5,10\]. The mean value is related to the attenuation coefficient \(\mu(E)\) by the following formula:

\[
\ln \left( \frac{I_0(y,z)}{I(y,z)} \right) = \left( \int \mu(l) \, dl \right)_{(y,z)},
\]

where \(I_0(y,z)\) and \(I(y,z)\) are the intensity of the X-ray beam in front and behind the test object, \((y,z)\) are the coordinates of the beam in the detector plane and the line integral is taken along the path of the beam through the object. The angle \(\alpha\), by which the X-ray beam is refracted by the object, is obtained by a generalized form of the equation adapted from \[8\]:

\[
\alpha = \frac{\lambda}{2\pi} \frac{\partial \Phi(y,z)}{\partial y} = \frac{\partial}{\partial y} \left( \int \delta(l) \, dl \right)_{(y,z)},
\]

where \(\Phi(y,z)\) is the phase shift of the X-rays at the plane of the phase grid \(G_1\). Here, the \((y,z)\) coordinates are measured in the plane of the phase grid. The measured quantity, i.e. the phase shift of the interference pattern \(\phi\), is related to \(\alpha\) by:

\[
\phi = 2\pi \frac{ad}{p_2} = 2\pi \frac{d}{p_2} \frac{\partial}{\partial y} \left( \int \delta(l) \, dl \right)_{(y,z)},
\]

where \(d\) is the distance between the phase grid \(G_1\) and the absorption grid \(G_2\), and \(p_2\) is the spatial period of the interference pattern at the plane of the absorption grid. For a single, homogenous material, the value of \(\delta(l)\) is constant and \(\phi\) is given by:

\[
\phi = 2\pi \frac{d}{p_2} \frac{\partial}{\partial y} \delta L_{(y,z)} \approx 2\pi \frac{d}{p_2} \frac{\Delta}{\Delta y} \delta L_{(y,z)},
\]

where \(L_{(y,z)}\) is the path length of the X-ray in the material, on which a discrete derivation is applied to obtain an approximation of \(\phi\). In the case of an object made of a single, homogenous material, following equation holds:

\[
\frac{\Delta}{\Delta y} \delta L_{(y,z)} = \frac{\delta}{\Delta y} \delta L_{(y,z)},
\]

where \(\Delta L_{(y,z)}\) is the difference of \(L_{(y,z)}\) between two locations on the DPC image separated by \(\Delta y\). Therefore Eq. (5) can be rewritten, for the case of a single, homogenous material, as follows:
\[ \phi \approx 2\pi \frac{d}{p_2} \frac{\Delta}{\Delta y} L_{(y,z)} = \phi_{\text{lin}} \Delta L_{(y,z)}, \]  

where \( \phi_{\text{lin}} \) is defined as follows:

\[ \phi_{\text{lin}} = 2\pi \frac{d}{p_2} \frac{\Delta}{\Delta y}, \]

The quantity \( \phi_{\text{lin}} \) is a measure of the sensitivity of the Talbot-Lau interferometer to a given material. It depends both on the material constant \( \delta \) and the parameters \( d, p_2 \) and \( \Delta y \) of the measurement setup (the step size \( \Delta y \) of the discrete derivation is given by the distance between two neighboring pixels). The ratio of \( \phi_{\text{lin}} \) to the linear attenuation coefficient \( \mu \) gives a value which determines the difference between the phase and attenuation contrast. Table 1 summarizes the values of \( \phi_{\text{lin}} \) and \( \mu \) obtained for six different plastics. The ratio of the coefficients is also listed.

### Table 1. Density, Decrement of the Real Part of the Complex Refraction Index \( \delta \), \( \phi_{\text{lin}} \), and Linear Attenuation Coefficient \( \mu \) of the Materials of the Test Object at 20.1 keV

| Material | Chemical Formula | Density \( \rho \) [g/cm\(^3\)] | \( \delta \) | \( \phi_{\text{lin}} \) | \( \mu \) | \( \phi_{\text{lin}}/\mu \) |
|----------|-----------------|-------------------------------|--------|----------------|-----|-----------------|
| PE       | CH\(_2\)        | 0.92 (0.93)                   | 5.46 × 10\(^{-7}\) | 16.5          | 0.162 | 102             |
| PA6      | NH-CO-(CH\(_2\)) | 1.14 (1.15)                   | 6.48 × 10\(^{-7}\) | 19.6          | 0.295 | 66.5            |
| PA66     | NH-CO-(CH\(_2\))…CO-NH-(CH\(_2\)) | 1.14 (1.14) | 6.48 × 10\(^{-7}\) | 19.6          | 0.295 | 66.5            |
| PMMA     | C\(_2\)H\(_4\)O\(_2\) | 1.19 (1.19)                   | 6.68 × 10\(^{-7}\) | 20.2          | 0.370 | 54.5            |
| POM      | CH\(_2\)O       | 1.41 (1.42)                   | 7.80 × 10\(^{-7}\) | 23.6          | 0.556 | 42.4            |
| PTFE     | C\(_2\)F\(_4\)  | 2.18 (2.16)                   | 1.09 × 10\(^{-4}\) | 32.9          | 1.50  | 21.9            |

- From the online polymer database of NIMS (National Institute for Materials Science, Japan).
- The values are from the webpage of the supplier, Angst & Pfister. The values in parentheses are our own measurements.
- Calculated with the help of formula (1) as described in [2,3] from the complex forward scattering factors found in the online database FFAST of NIST (National Institute of Standards and Technology, USA).
- Calculated for \( d = 69.3 \) mm, \( p_2 = 3 \) \( \mu \)m, and \( \Delta y = 48 \) \( \mu \)m.

Differential phase clipping in the DPC image occurs where the second derivative of the phase of the X-ray wave front is important. Differential phase wrapping occurs where the X-ray beam is refracted strongly enough to lead to a phase shift of the interference pattern which exceeds \( 2\pi \). In both situations, the AC signal also varies strongly and, therefore, can be used to correct the DPC image: Where differential phase wrapping and clipping occur, the DPC values are replaced by the discrete derivation of the logarithm of the AC signal, i.e. the discrete derivation of the line integral of the attenuation coefficient, multiplied by the ratio \( \phi_{\text{lin}}/\mu \). The locations of possibly bad pixels in the DPC image can be identified in the AC image: Every pixel where the difference between the logarithms of the AC values of its left and right neighbors is bigger than twice a threshold \( T \) is chosen to localize a pixel in the DPC image which has to be corrected. The pseudo-code below describes the correction algorithm:

```plaintext```
for i = 1 to number of image rows do
  for j = 1 to number of image columns do
    if abs((ln(AC image (i,j−1)) − ln(AC image (i, j + 1))/2) > threshold do
      DPC image (i,j) = \( \phi_{\text{lin}}/\mu \) • (ln(AC image (i,j−1)) − ln(AC image (i, j + 1)))/2;
```

3. Experimental setup

The DPC measurements were accomplished with the help of a cone beam X-ray CT setup and three X-ray gratings in a Talbot-Lau configuration [7,9,10]. The measurements were performed on an instrument installed at the CSEM facilities [14]. The geometric setup is illustrated in Fig. 1(a):
The source grid $G_0$ and the analyzer grid $G_2$ were made of gold, and the phase grid $G_1$ was made of silicon. The periods of the grids $G_0$, $G_1$ and $G_2$ were 57 \( \mu \text{m} \), 2.85 \( \mu \text{m} \) and 3 \( \mu \text{m} \), respectively. Their structure heights were 60 \( \mu \text{m} \), 12.7 \( \mu \text{m} \) and 30 \( \mu \text{m} \), respectively. The duty cycles of the grids $G_0$, $G_1$ and $G_2$ (defined as the ratio of the openings or trenches over the periodicity) were 0.5, 0.5 and 0.3, respectively. The pixel spacing of the camera was 48 \( \mu \text{m} \).

The acceleration voltage and the current of the X-ray source were set to 40 kV and 22.5 mA, respectively. 722 DPC images of the object and 45 flat images were recorded at different angles distributed evenly over 360°. At each angle, the interference pattern was measured by a scan with 10 phase steps, i.e. by translating the source grating $G_0$ over a total distance of 57 \( \mu \text{m} \). The exposure time for each step was 6.7 s which resulted in a total measurement time of 21 h. All projections were corrected by the corresponding flat and dark fields [1]. The 3D DPC and AC images of the object were reconstructed with a Feldkamp algorithm [1,12,15].

For studying DPC CT artifacts we produced a test sample of cubic shape (30 x 30 x 30 mm$^3$) assembled from six pyramids made of different plastics (PE, PA6, PA66, PMMA, POM, and PTFE). A test chart (based on ISO 12233) was imprinted on each pyramid by means of laser ablation (Fig. 1(b)). The six pyramids were glued together using a two-component adhesive (Loctite® 406 and 770).

### 4. Result of the phase artifact reduction

In order to judge the merit of the proposed method for the reduction of phase clipping artifacts we carried out a DPC CT measurement of a plastic cube (Fig. 1(b)). The flat surfaces and pronounced edges give rise to fast differential phase changes and strong artifacts in the reconstructed image. In principle, the proposed phase unwrapping method has to take into account the refractive index of the different materials. Theoretically, this ratio depends on the combination of materials at each interface. In our experiment, it turns out that taking a single value ($\phi_{\text{lin}}/\mu_{\text{ph}} = 21.9$), corresponding to the interface between the material with the highest refractive index (PTFE) and air, gives good results. Figure 2 shows a region of a projected DPC image with strong differential phase clipping and wrapping (Fig. 2(a)), the corresponding AC projection (Fig. 2(b)) which is used for the correction and the corrected DPC image (Fig. 2(c)). The AC images were filtered by applying a median filter with radius 1 (i.e. the median of the values of the pixel and its 8 nearest neighbors was taken) prior to the localization of possibly bad pixels in the DPC image. Bad pixels were located by applying the algorithm described in section 2: A value of 0.02 was chosen for the threshold parameter T. For a lower threshold, noise and errors in the AC image lead to false positives, i.e. erroneously corrected phase values. A too high threshold results in false negatives, i.e. pixels with incorrect phase values are not identified. The effect of the suggested procedure on projections (Fig. 2(a), 2(b) and 2(c)) and sinograms (Fig. 2(d), 2(e) and 2(f)) is illustrated in the top and bottom rows of Fig. 2, respectively.
Differential phase wrapping or clipping in the projection images will lead to artifacts in the reconstructed 3D distribution of the refractive index, as shown in Fig. 3(a), 3(b), 3(c) and in Fig. 4(a). Figure 3(d), 3(e), 3(f), and Fig. 4(b) show the same slices after correction.

The corrected images show reduced phase clipping artifacts. For example, an imaginary material appears in the gap between two parts of the test object in the uncorrected phase image (Fig. 3(a)). In the corrected image (Fig. 3(d)), the gap is visible with its actual shape again. The shadows casted by the dense PTFE pyramid are also due to phase errors (Fig. 3(b)). After correction, the shadows disappear (Fig. 3(e)), although a slight overcorrection is visible. Gaps in the material cause stripe artifacts in the uncorrected image (Fig. 3(c)), which are less visible in the corrected image (Fig. 3(f)).
Since the AC projections are used for the phase unwrapping, any errors in the AC signal propagate into the reconstructed 3D distribution of the refractive index, as is illustrated in Fig. 4: At the top edges, the AC image (Fig. 4(c)) shows severe beam hardening artifacts and, therefore, the correction of the DPC image (Fig. 4(b)) fails. A comparison of zoomed in regions of the absorption (Fig. 4(d)) and phase (Fig. 4(e)) images reveals that the phase image has a slightly lower spatial resolution than the absorption image.

Fig. 4. One of the surfaces (PE) of the cube reconstructed from the uncorrected (a) and corrected (b) DPC projections, and the AC projections (c). (d) and (e) are zoomed in regions of the absorption (c) and phase (b) images, respectively.

Whereas the AC image has superior quality than the DPC image in regions where the AC contrast is good the contrary is true in regions of low AC contrast, as can be seen in Fig. 5:

Fig. 5. Comparison between DPC (a) and AC (b) images in a region where the attenuation contrast is worse than the phase contrast. The images show the glue between two neighboring pyramids. The AC image is noisier and the voids in the glue are not as visible as in the DPC image. Also the visibility of the numbers is impaired by the noise of the AC image, whereas some numbers can be deciphered in the DPC image.

Figure 5 shows a cross section of the two-component adhesive which was used to glue together the pyramids of our test object. It turns out that the density of the glue is not uniform and that the structure which was engraved on the surface of one pyramid is reproduced in the glue. The AC image (Fig. 5(b)) is much noisier than the DPC image (Fig. 5(a)) and the small voids in the glue are much less visible in the AC image than in the DPC image. Also the numbers can be more easily deciphered in the DPC image than in the AC image.

5. Conclusion

DPC CT images of objects can show strong artifacts like shadows, stripes and imaginary structures. These artifacts are caused by incorrectly determined values in the DPC projections. Actually, a few bad pixels suffice to cause severe artifacts in the reconstructed 3D distribution of the refractive index. Based on the observation that incorrect DPC values occur exclusively at locations where the AC is high we propose to use the AC projections for correcting the DPC projections. The proposed correction method is applied on a DPC CT measurement of a test cube made of different plastic materials. Considerable reduction of the phase artifacts is
demonstrated. The efficiency of the method is limited by the quality of the AC images and can, therefore, be improved by reducing the noise and artifacts in the AC images.

Our correction method allows for DPC CT measurements of samples causing phase artifacts which would be infeasible otherwise.

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