Phase alteration compensation in reflection digital holography

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Abstract. The phase maps obtained from digital holographic microscopy techniques carry information about the axial lengths of the object under study. Additionally, these phase maps have information of tilt and curvatures with origin in the off-axis geometry and the magnification lenses system, respectively. Only a complete compensation of these extra phases allows a correct interpretation of the phase information. In this article a numerical strategy to compensate for these alterations is designed, using a phase mask located in different planes. This strategy is applied in the measurement of a phase steps plate using a digital holography setup.

1. Introduction
In the last decade, the Digital Holographic Microscopy (DHM) has shown to be a practical tool for some metrological applications like the measurement of metallic spheres [1], semiconductor material surfaces [2], and a variety of micro-electromechanical elements in silicon [3, 4]. In the case of reflective objects, numerical phase information can be obtained from the optic field and this phase can be understood as topography differences in the object.

Nevertheless, this interpretation must take into account the contribution to the optical path length from both the off-axis geometry and the curvature in the field created by the magnification lenses system (see Figure 1).

A condition to eliminate or compensate for the effects of these additional optical path numerically, is to know a-priori all the experimental parameters that define it. In this sense, some techniques have been published in which the optical field is manipulated, and the information about the parameters is recovered [5, 6].

In this article a numerical strategy to compensate for the phase alterations in reflection digital holography is shown. This strategy uses two phase masks. Their construction requires a manual manipulation over both the hologram plane and the image plane. These phase masks are fundamentally complex matrices with constant amplitude that are multiplied point by point with the matrix that represents the optical field.

In the following sections, an experimental hologram is used to illustrate all the strategy steps. At the end, the numerical strategy is successfully applied to determine the depths of the steps recorded on a photoresist-coated glass plate.

2. Strategy for numerical compensation
Double exposure is one of the most used techniques for compensation of phase alterations [7]. In this technique it is necessary to construct a phase mask using an experimental hologram
**Figure 1.** Experimental setup for digital holographic microscopy using reflective objects. The laser is \(He-Cd\) of 442 nm, \(M\) is a mirror, \(CL\) is a collimating lens, \(L1\) and \(L2\) represent a lenses system with magnification of 8.5× (compound by a doublet of 50 mm of focal distance and a 5× JIS objective) and \(BC\) is a Non-Polarizing Beam-splitter Cube. A CCD camera was used for the acquisition of the images. The pixel pitch of the CCD was 7.5 \(\mu m\).

**Figure 2.** Digital recording of the hologram (640 × 480 pix). Here the object is a series of bars from the element 1, group 2, of a metallic copy of the USAF-1951 test target. Each bar is 125 \(\mu m\) wide. The distance of propagation corresponds to 30 mm.

without information about the object. In the case of reflection digital holograms, experimental conditions hinder the application of this double exposure technique and because of this, it is recommended to generate the phase mask using only one recorded hologram (see Figure 2). A condition for the generation of the phase mask, in the case of reflective objects, is the possibility to define "flat regions" (without object information), that are included in the same hologram.

If this condition is true, the first step for the phase mask construction is a numerical fit of these regions.

The design of the phase mask follows a basic schema of four points:

(i) **Selection of a flat region:** It is necessary to select regions without object information. All regions selected must be connected to prevent losses in their phase relations.

(ii) **Application of a phase unwrapping in the region selected:** this method must successfully resolve discontinuities in the phase with high frequencies in presence of speckle noise.

(iii) **Polynomial fit of the unwrapped phase:** the phase map \(\phi(x, y)\) requires a non-linear fit to interpolate the phase present in the flat portion of the object. In this way, the polynomial fit will have the form: \(\phi(x, y) = \sum_{\alpha=0}^{A} \sum_{\beta=0}^{B} C_{\alpha\beta} x^\alpha y^\beta\), where \(A\) and \(B\) are the orders of the polynomial.

(iv) **Phase Mask construction from the polynomial fit:** the polynomial fit is used as the argument of a complex field. This field is generated as \(\Gamma(x, y) = \exp\{ -i \phi(x, y)\}\).
To compensate the off-axis holograms phase, the numerical strategy requires the use of two phase masks: the first one is located in the hologram plane and the second one is located in the image plane.

![Figure 3](image)

**Figure 3.** Implementation of the four steps for phase mask generation in the hologram plane. (a) Selection of a flat region. (b) Phase unwrapping in the selected region. (c) Polynomial fit of the unwrapped phase. (d) Argument of the complex mask. (e, f) Amplitude and phase in the hologram plane after applying the phase mask. The application of this phase mask allows a numerical field without tilt which makes it possible for some structures in the phase image to be visible.

The idea of the first mask (Figure 3) is to generate the best numerical approximation of the field that represents the reference wave used for the holographic recording. As a result of multiplying the optical field by the conjugate of this mask, a numerical field without tilt is obtained.

Similar results for the phase image in the hologram plane (see Figure 3f) can be obtained applying the discrete Fourier transform method with a spectrum shift process [8]. However, unlike the implementation of the phase mask, this spectrum technique have a drawback with the integer pixel accuracy for the spectrum shift which generates residual errors in tilt correction [9].
Figure 4. Phase mask generation in the image plane. (a) Selection of a flat region. (b) Phase unwrapping in the selected region. (c) Polynomial fit of the unwrapped phase. (d) Argument of the complex mask. (e, f) Amplitude and phase in the image plane after applying the phase mask. After the application of this phase mask, a compensated version of the numerical field is obtained, generating a discontinuous phase version proportional to the object topography.

The phase of the optical field in the image plane is obtained by numerically propagating this corrected field, using the angular spectrum method [10] (Figure 4a). In this plane, a second complex mask is constructed, whose argument represents a surface that fits the residual tilt, curvature and additional phase alterations generated by the introduction of the magnification optics (Figure 4(e-f)).

Although the implementation of proposed numerical strategy is not completely automatic, one of its main advantages is the construction of the phase mask using only information of the polynomial fit. In this case, unlike the methods proposed in references [11, 12] trial and error processes to find the parameters of a tilt or curvature numerical model are not needed.

In Figure 5 the compensated phase map after an unwrapping process is shown [13]. In this image the phase discontinuities have been properly resolved.

Figure 5. Phase corrected with an additional phase unwrapping.
3. Experimental result
The compensation method was applied to measure a phase step. This phase object was constructed on a photoresist coated glass plate. This plate was first exposed to a light source while a mask was moved over its surface in 100 $\mu$m steps. After the developing process, the sample surface was metalized by spraying the plate with a silver compound.

Figure 6 shows the holographic recording of the phase step made with the setup of Figure 2. This image is $1024 \times 480$ pixels in dimension and is compound by two adjacent holograms of $640 \times 480$ pixels. Due to its flatness, the right side of the hologram was used in the construction of the phase masks.

![Figure 6. Digital hologram recorded using a phase steps plate.](image1)

The corrected phase image was obtained after applying the numerical strategy of two masks. A section of the topography image, located just above the region of the phase steps is shown in Figure 7.

Table 1 shows the comparison between the measured depths obtained by the DHM method and a contact profilometry method in which a Veeco Dektak profilometer 150 was used.

![Figure 7. Tridimensional representation of the object topography.](image2)
Table 1. Comparison between the corrected DHM results and the profilometer results. Each step was numbered from left to right direction, according to Figure 7.

| Step | Corrected phase measurement ($\mu$m) | Profilometer measurement ($\mu$m) | Percentage difference(%) |
|------|-------------------------------------|----------------------------------|---------------------------|
| 1    | 0.213 ± 0.021                       | 0.220 ± 0.022                    | 2.9                       |
| 2    | 0.358 ± 0.035                       | 0.350 ± 0.024                    | 2.4                       |
| 3    | 0.279 ± 0.028                       | 0.281 ± 0.025                    | 0.5                       |
| 4    | 0.264 ± 0.026                       | 0.259 ± 0.024                    | 2.7                       |
| 5    | 0.244 ± 0.024                       | 0.235 ± 0.025                    | 4.0                       |
| 6    | 0.194 ± 0.019                       | 0.221 ± 0.016                    | 12.0                      |

4. Conclusions
The numerical implementation of the strategy to compensate phase alterations such as tilt and curvature demonstrated its feasibility. This strategy allowed a correct interpretation of the phase maps that have been obtained from a reflective version of a USAF 1951 test target.

Also, some depth measurements were obtained by the use of the application of the numerical strategy. These results were compared with the measurement of the same object obtained by a contact profilometer, giving successful results.

As an application perspective, the numerical manipulation of the phase will provide measurements with interferometric precision in the future, without mandatory use of highly corrected optical surfaces.

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