

Research Article

Combined Reduced Phase Dual-Directional Illumination Digital Holography and Speckle Displacements for Shape Measurement

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We present a digital holographic method to increase height range measurement with a reduced phase ambiguity using a dual-directional illumination. Small changes in the angle of incident illumination introduce phase differences between the recorded complex fields. We decrease relative phase difference between the recorded complex fields 279 and 139 times by changing the angle of incident 0.5° and 1° , respectively. A two cent Euro coin edge groove is used to measure the shape. The groove depth is measured as $\approx 300 \mu\text{m}$. Further, numerical refocusing and analysis of speckle displacements in two different planes are used to measure the depth without a use of phase unwrapping process.

1. Introduction

Noninvasive characterization of surface shape and deformation is very important in many industrial applications such as on-line quality control and reverse engineering [1]. Digital holography is well known for producing high precision noninvasive shape measurements [2]. It gives the possibility to numerically propagate the field to different distances from the detector, in order to do the numerical postprocessing [2–6]. However, when phase variation spans more than 2π in a measured field, it results in phase ambiguity. To remedy this problem, different methods have been presented [7–15]. Numerical methods are often used to solve the problem [9]. However, they are usually time consuming and are not suitable for real-time measurements. Multiwavelength Interferometry (MWI) is another solution which, in the form of a single shot (multiplexed), can be used for real-time measurement purposes [7, 10–15]. The maximum measurable range in MWI is limited by the synthetic beat wavelengths of a system. However, chromatic aberration in MWI and pseudophase changes in the multiplexed (single shot) form are inevitable sources of error that need to be suppressed and calibrated [4, 16–21]. Dual-directional illumination quantitative phase imaging with a single wavelength light source

is another unwrapping solution [22–26]. Two independent interferograms with different illumination directions can be recorded by changing the angle of incident laser light with a tilting mirror. The method is based on reducing the measured phase to less than 2π . As the method uses a single wavelength light source, there is no error due to the chromatic aberrations. Although this method usually requires two different images to be obtained consecutively within a certain time interval, they can also be obtained in a single shot method in order to be used in real-time measurements [26]. In addition to the above methods, when measuring the shape of an optically rough object, the movement of the speckle pattern in different refocusing distances can be analyzed [27–30]. Correspondence between speckle displacements and phase gradients [5, 31] can be utilized to find the shape without problems with phase unwrapping.

In this study, we combined a reduced phase dual-directional illumination and analysis of speckle displacement methods to be used together for a large stepped sample without phase wrapping in the reconstructed data. A combination of two methods can make a robust system since the analysis is not only based on phase differences but is also based on speckle displacements.

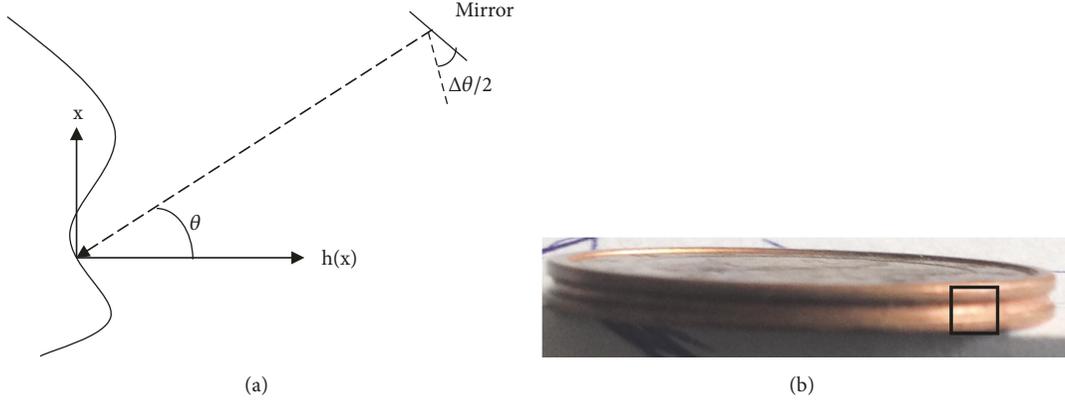


FIGURE 1: Schematic of simplified set-up for dual-direction illumination shape measurement (a). The measured coin edge (b). The squared area has been recorded and used for measurement.

2. Theory of Reduced Phase Dual-Directional Illumination Holography

For measurement of the shape we take the difference between the reconstructed phases which are recorded before and after a small tilt $\Delta\theta$ of the object illuminating beam. Consider the simplified set-up depicted in Figure 1(a). The mirror reflects the laser beam to the object surface with an initial angle of θ . For simplicity, we adopt two-dimensional analysis. The reconstructed phase will then be expressed by

$$\phi_1(x) = k [x \sin \theta + h(x) \cos \theta], \quad (1)$$

where $k = 2\pi/\lambda$ and $h(x)$ mean the surface height from the reference plane. In the second stage, we tilted the mirror at an angle of $\Delta\theta/2$ from the initial angle of incidence θ . The reconstructed phase in this stage will then be

$$\phi_2(x) = k [x \sin(\theta + \Delta\theta) + h(x) \cos(\theta + \Delta\theta)]. \quad (2)$$

Hence the phase difference becomes in terms of θ and $\Delta\theta$ as

$$\begin{aligned} \Delta\phi(x) &= \phi_2(x) - \phi_1(x) \\ &= k [x \sin(\theta + \Delta\theta) + h(x) \cos(\theta + \Delta\theta)] \\ &\quad - k [x \sin(\theta) + h(x) \cos(\theta)] = 2k \sin \frac{\Delta\theta}{2} \\ &\quad \cdot \left[x \cos \left(\theta + \frac{\Delta\theta}{2} \right) - h(x) \sin \left(\theta + \frac{\Delta\theta}{2} \right) \right]. \end{aligned} \quad (3)$$

Therefore we can determine the object shape $h(x, y)$ that results from the difference between the reconstructed phases ϕ_1 and ϕ_2 which are recorded before and after a small tilt $\Delta\theta$ introduced in the object illumination beam. $\Delta\phi$ is related with the change in optical path length sensitivity of the set-up which is given by the geometrical optics arrangement; actually it is determined by the illumination and observation direction. Here, in this set-up, the observation direction is fixed and the illumination direction is changed by the angle of $\Delta\theta$.

The sensitivity of the set-up (height range measurement) for having unwrapped phase can be then calculated as

$$0 \leq 2k \sin \frac{\Delta\theta}{2} h(x) \sin \left(\theta + \frac{\Delta\theta}{2} \right) \leq 2\pi, \quad (4)$$

which leads to the maximum range of height that can be measured without phase wrapping as

$$h(x, y) \leq \left| \frac{\lambda}{2 \sin(\Delta\theta/2) \sin(\theta + \Delta\theta/2)} \right|. \quad (5)$$

Comparing (5) with the conventional maximum range of height $\lambda/2$ shows that we increase the height range by the factor of $1/\sin(\Delta\theta/2) \sin(\theta + \Delta\theta/2)$. Therefore we have a scaling (phase reduction) factor of $\sin(\Delta\theta/2) \sin(\theta + \Delta\theta/2)$.

Therefore the shape of the object will be measured by

$$h(x, y) = \frac{\lambda\phi(x, y)}{4\pi [\sin(\Delta\theta/2) \sin(\theta + \Delta\theta/2)]} \quad (6)$$

If the illumination angle is parallel with the optical axis, $\theta = 0$ and the phase reduction factor will then be $(1 - \cos \Delta\theta)/2$. Therefore (5) will change to

$$h(x, y) = \left[\frac{2}{1 - \cos \Delta\theta} \right] \frac{\lambda\phi(x, y)}{4\pi}. \quad (7)$$

3. Experimental Results

We choose a 2 cent Euro coin to measure the groove depth of its edge. A laser beam with the wavelength of 532.35 nm was used to illuminate the test object. The interference pattern was recorded by a high resolution CCD camera (Vistek, Eco655) with 2448×2050 pixels of the size 3.45×3.45 μm pitch with a set-up magnification of $M = 3.2$. The angle of incident was $\theta = 55^\circ$ with respect to the optical axis, and its changes were $\Delta\theta = 0.5^\circ$ and 1° leading to the height sensitivity $\Delta h = 74 \mu\text{m}$ and $37 \mu\text{m}$, respectively. These changes resulted in the distribution of the reconstructed phase difference shown in Figure 2.

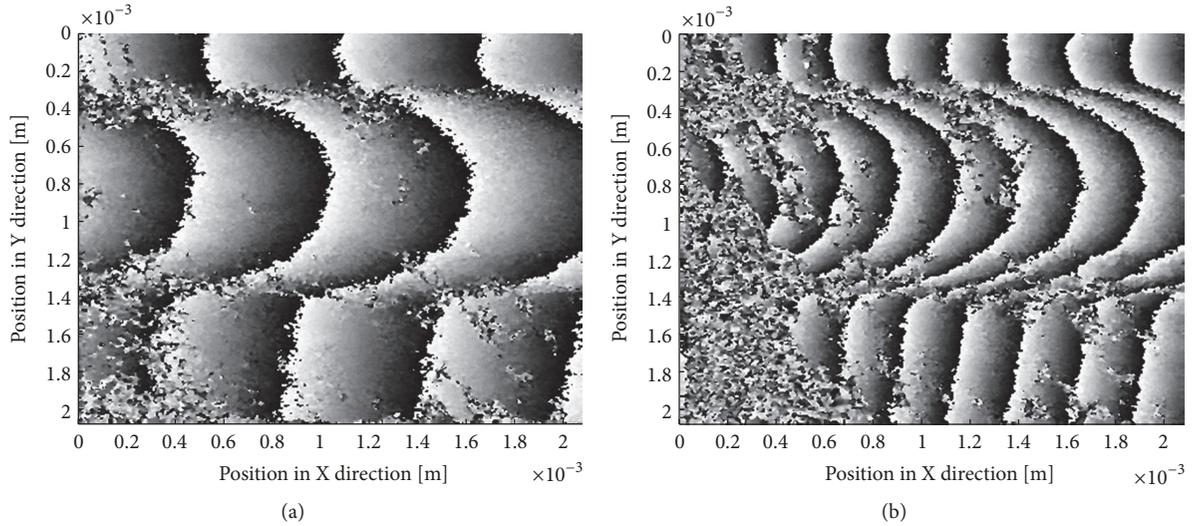


FIGURE 2: Reduced phase distribution as a result of small change in the angle of incident. Scaling (phase reduction) factor is 279 in (a) and 139 in (b).

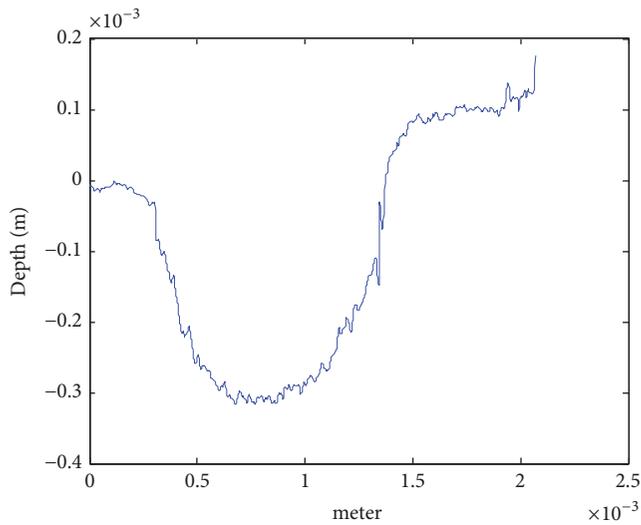


FIGURE 3: A vertical cross section over the measured shape of the groove in coin edge.

Using $\Delta\theta = 0.5^\circ$ and 1° , the phase reduction factors are 279 and 139. In Figure 2(a) height sensitivity is almost twice of Figure 2(b). This is why the number of wraps in Figure 2(a) is two times less than Figure 2(b). An arbitrary cross section from the unwrapped phase map is used to measure the depth of the groove in the coin edge. Figure 3 shows a plot of the cross section over height profile. We measured the groove depth of $h \approx 300 \mu\text{m}$ for the coin.

We have also used speckle displacements to measure the height (depth), independent of phase information which leads to a solution without being in a need for unwrapped phase information; see [30, 31]. The complex amplitudes from

the recorded holograms were then acquired and used to calculate two more sets of complex amplitudes using numerical refocusing. One field is set 10 mm behind the object and the other 10 mm in front of the object. We hence have six complex amplitudes acquired at two illumination directions (55° and 55.5°) originating from three different planes, which are used to acquire information of the depth on the object edge. Position of the focus plane plays a crucial role in order to detect the shape of the object. According to the speckle displacement behavior, on the surface of the object, when it is on the focus plane, there are no speckle displacements. The reason is that speckle displacements induced by the phase gradients do not appear in the focus plane; see [5, 29]. It is worth mentioning that, in the speckle displacement based method, the dominant parameter affecting the accuracy of the measurement is the accuracy of the speckle displacement calculation that is a function of the speckle correlation itself [32–34]. This is why the numerical refocusing must be well below the range of the longitudinal speckle size in order to avoid higher decorrelations.

Figure 4 shows the speckle displacements in pixels in three different planes while average correlation is 0.78. Different parts of the object show different sizes of the speckles since they are located in different planes because of object surface height change. Since the speckle displacements follow linear behavior, fitting first order of the polynomial function to the speckle displacements as a function of refocusing distance retrieves the shape of the object. Consequently, the depth (height) of the object can be calculated without being in a need for phase unwrapping process. Figure 5 shows the results from the speckle displacement analysis. Height profile is seen in (a) with an inverted cross section over a horizontal direction (b) which shows the measured depth. Depth groove of $h \approx 340 \mu\text{m}$ is calculated using speckle displacements method.

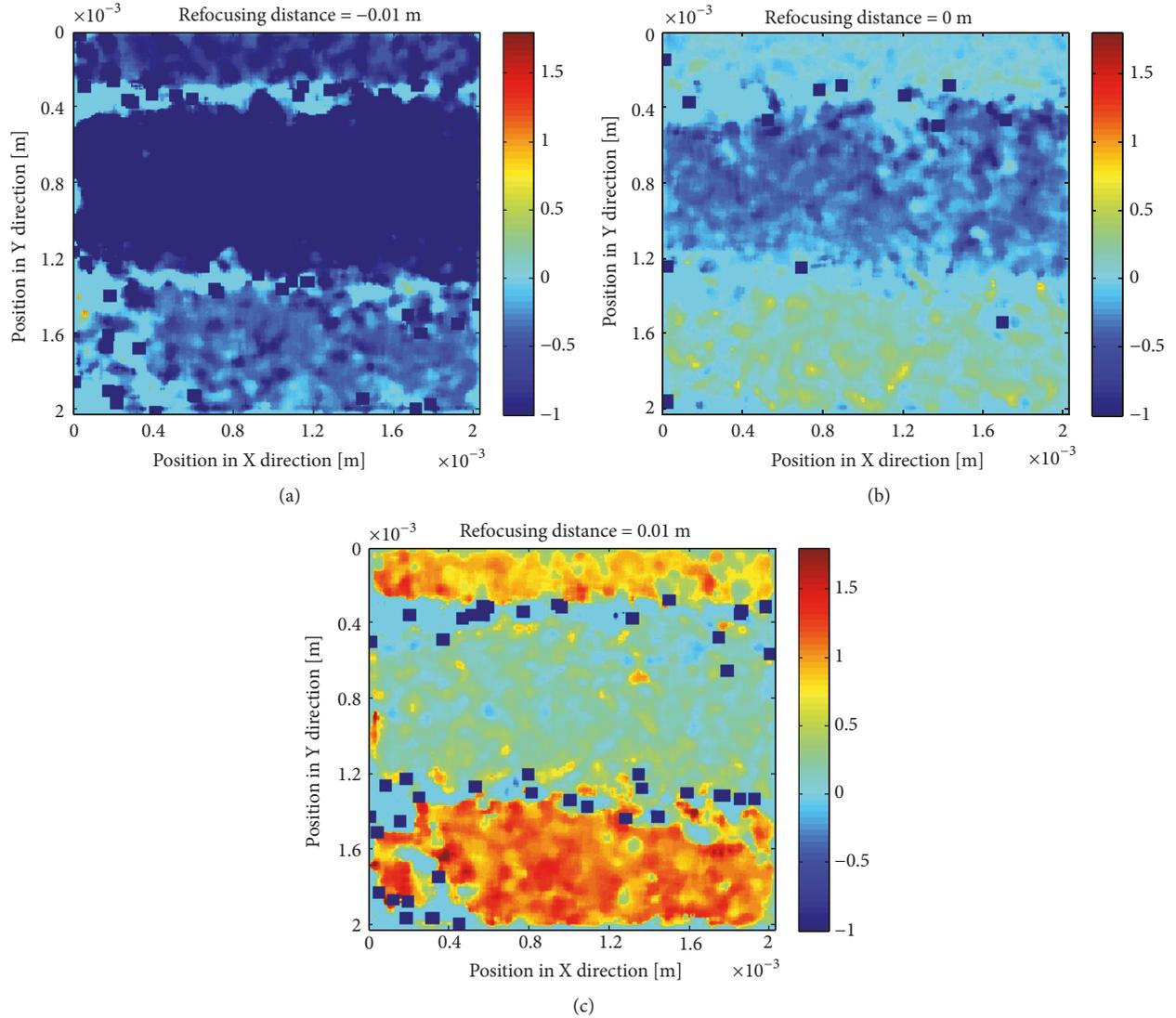


FIGURE 4: The speckle displacement map 10 mm behind the object, on the object plane, and 10 mm in front of the object in (a), (b), and (c), respectively.

4. Conclusion

We have shown that, by introducing a small change on the angle of incident, it is possible to scale the phase difference between two recorded complex fields. Therefore, adjustment of phase reduction factor will give a possibility to keep the phase difference in the range of 2π ; thus there is no phase wrapping ambiguity that makes it possible to measure height discontinuities. Further, it is shown that it is possible to use speckle displacements as a result of change in the sensitivity vector [27–29] originating from small change of the angle of incident. Using speckle displacements provides a method that is independent of phase unwrapping. The presented results are preliminary which shows measurement difference of $40 \mu\text{m}$. However, an accurate measurement can be achieved using noise and error reduction algorithms that are out of the scope of this study.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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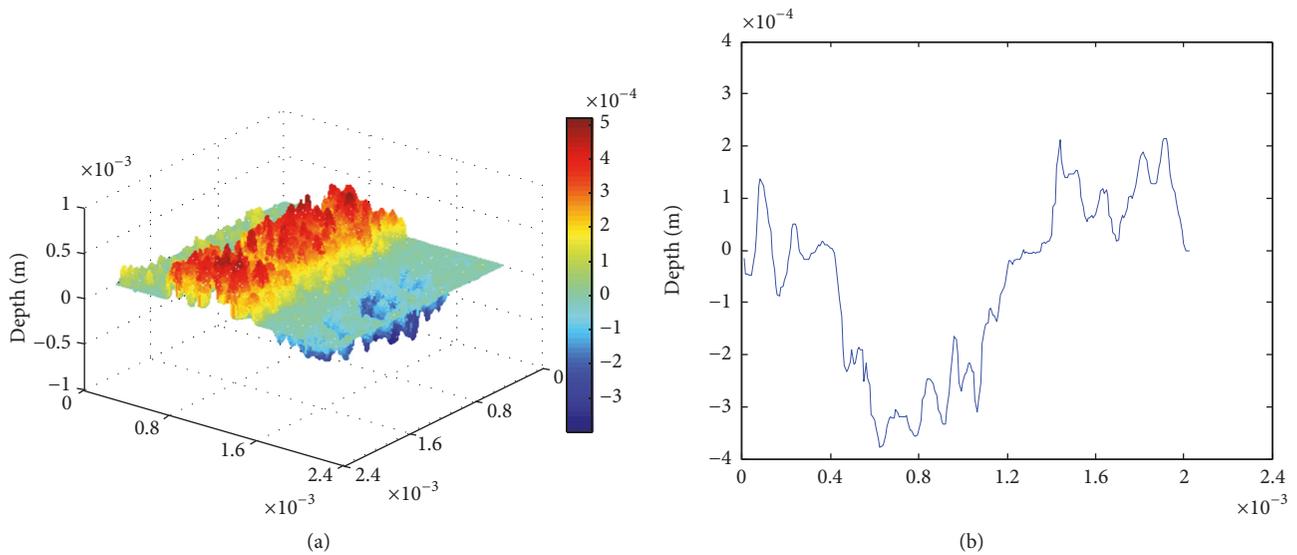


FIGURE 5: Depth measurement using speckle displacement calculations. (a) is the height profile and (b) is an inverted cross section over a horizontal line.

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