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Efficient and Exact Extraction of the Object Wave in Off-axis Digital Holography

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In this paper, a new method for spatial filtering in digital holography is proposed and verified by simulations compared to conventional methods. The new method is based on the simultaneous acquisition of two digital holograms, which can be separated by distinct spatial modulation, in a single image. Two holograms are generated by two reference waves, which have different spatial modulation orientations. Then, the overlapping region between the DC term and the object wave in the first hologram can be replaced with a less-overlapping region of the object wave in the second hologram because the whole image contains two holograms where the same objective wave has been recorded. In the simulation results, it is confirmed that the reconstructed image by the new method has better quality than for the original method.

Keywords : Off-axis digital holography, Image reconstruction techniques, Optical metrology
OCIS codes : (090.1995) Digital holography; (100.3010) Image reconstruction techniques; (120.3940) Metrology

I. INTRODUCTION

In contrast to normal techniques, digital holography (DH) is an effective tool to record not only the amplitude image but also the phase image. The main advantage of DH obviously originated from the real time 3D measurements of the target with a single image only [1]. In addition, DH has the capability to reconstruct the amplitude and phase of the object wave even though the specimen is not in the best focus or the optical system includes aberrations [2, 3]. Based on these advantages, DH has been widely used in industrial and science fields, especially in biomedical fields where the amplitude and phase images of live cells should be monitored in real time [4]. In manufacturing industrial products, DH can raise the throughput significantly through the real time inspection of the products topographically as well as tomographically.

Digital holography can typically be categorized into two, off-axis DH and in-line DH, according to the optical configuration, i.e. the alignment between reference and object waves. In order to extract the object wave term from the hologram, off-axis DH uses a spatial modulation and spatial filtering technique with a tilt angle between reference and measurement waves [5]. Without any efforts in-line DH might take to eliminate these noise effects, off-axis DH can reconstruct the amplitude and phase image of the specimen from the hologram. On the other hand, in-line DH typically adopts other techniques such as phase shifting to extract the object wave from the hologram [6]. Because of this inherency, in-line DH loses the real time measurement ability in its applications although it can reconstruct the image clearly. Recently, in order to overcome this limitation, parallel optical-path-length-shifting DH based on a spatial phase shifting device has been proposed for real time measurements [7]. However, this method is limited by the available number of pixels in the CCD camera.

One of the most important procedures in off-axis DH is the spatial filtering process to eliminate other terms, i.e. a DC term (zero-order) and a twin image term (conjugate wave) in the spatial frequency domain in order to obtain the high quality object wave from the digital hologram. T. M. Kreis introduced a simple method to suppress the DC term from the hologram [8]. This method consists of subtracting the mean intensity from the digital hologram, which permits the elimination of only the so-called DC term from the reconstructed images. It’s a simple way to

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reduce the DC terms from the hologram but it's not sufficient in most of cases. For the improvement, E. Cuche proposed the approach known as spatial filtering in the form of a band-pass filter [9]. The method depends on the critical assumption that the DC term and the desired term are well separated so that the DC term can be suppressed by filtering. However, they are also limited by two other aspects; one is that only the small portion of the spectrum can be available because of the spatial filtering and the other is that the spatial filtering often requires manual intervention for selecting the desired order. Another method to achieve the effective filtering was patented using additional images [10]. In this method, the reference wave intensity and object wave intensity are obtained in addition to the hologram in the system and these are used for removing the DC terms of the hologram by simple subtraction. However, it needs additional hardware such as beam blockers and two more images should be recorded. In this case, it is assumed that the environmental conditions and system parameters should be kept constant.

Recently, a nonlinear reconstruction technique has been introduced [11]. This enables the exact zero-order free reconstruction in off-axis DH even if the zero-order and the object wave spectra overlap. The nonlinear filtering technique works under two assumptions on the digital hologram; first, the spectrum of the object wave should be confined to a quadrant of the Fourier domain and second, the intensity of the object wave should be much smaller than that of the reference wave. However, the small intensity of the object wave can lower the visibility of the interference fringe and even lower a signal to noise ratio (SNR), which can cause other errors. It means the effectiveness of this method can be limited in practical applications. On the other hand, the suppression of the zero-order term by employing the information obtained during wave front reconstruction in an iterative procedure was reported [12]. It enables the DC term suppression without any prior knowledge about the object. However, this technique takes the calculation time until reaching to an acceptable error level.

In this paper, a novel and effective spatial filtering technique to extract the exact object wave in off-axis DH is proposed. The new method for spatial filtering is based on the simultaneous acquisition of two digital holograms, which can be separated by their distinct spatial modulation, in a single image. Consequently, the overlapping region between the DC term and the object wave in the first hologram can be replaced with a less-overlapping region of the object wave in the second hologram because the whole image contains two holograms where the same objective wave has been recorded.

II. PRINCIPLE

In the proposed method, two reference waves (R_1 and R_2), which have different spatial modulation directions, are used for recording digital holograms. This is contrary to conventional off-axis DH which typically uses only one reference wave. Then, each reference wave can generate each interference fringe with the object wave. It is noted that the interference between two reference waves should not be included in this image. It can be implemented in practice by using orthogonal polarized reference lights, for example, as shown in Fig. 1.

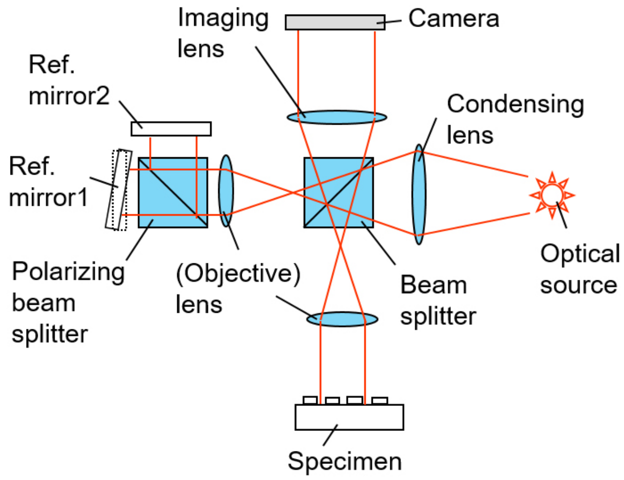


FIG. 1. An example of the optical configurations used to avoid the interference between two reference waves for the proposed method.

As a result, the image (I_{2H}) containing two holograms in this method can be expressed as

$$I_{2H}(x,y) = |R_1|^2 + |O|^2 + |R_2|^2 + |O|^2 + R_1^*O + R_1O^* + R_2^*O + R_2O^* \tag{1}$$

The first four terms of Eq. (1) mean the zero-order diffraction (or DC term) in the spatial frequency domain. The fifth and sixth terms are interference terms by R_1, and their spatial frequencies are located symmetrically with respect to the center in the spatial frequency domain. The seventh and eighth terms are the interference terms by R_2, and their spatial frequencies are also located symmetrically. In this case, these four interference terms can be spatially separated in the spatial frequency domain due to the different spatial modulations of R_1 and R_2.In particular, it is preferred in this method that each term is located in each quadrant of the domain adjusting the tilts of the reference mirrors as shown in Fig. 2(b).

In fact, the main difficulty to extract the object wave in conventional off-axis DH [9] is caused by the overlapping region between the DC term and the object wave term in the spatial frequency domain as shown in Fig. 2(a). In the proposed method, however, the overlapping region between the DC term and the object wave in the first hologram can be replaced with less or no overlapping region of the object wave in the second hologram because the image

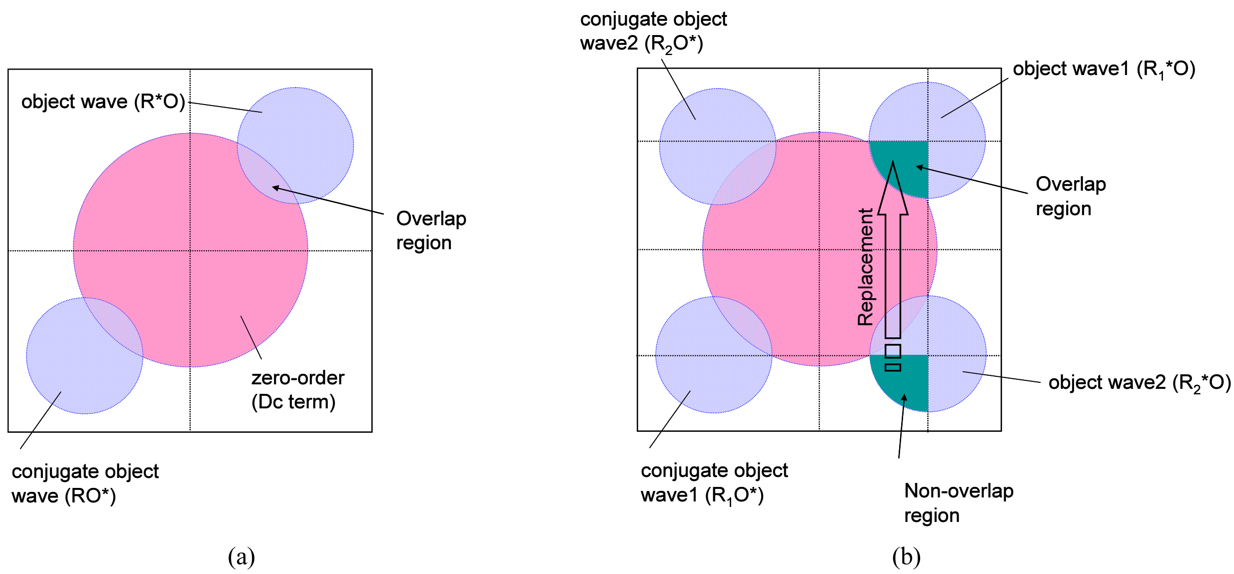


FIG. 2. (a) Spatial frequency contents of a conventional digital hologram; each circle means the spatial frequency contents involved in each term. (b) Spatial frequency contents of two digital holograms in this method; each circle means the spatial frequency contents involved in each term. The overlap region of $R_1{*}O$ can be replaced with the non-overlap region of $R_2{*}O$.

contains two holograms where the same objective wave is recorded. For example, the overlapping region of $R_1{*}O$ (left-down quadrant of the object wave, $R_1{*}O$ frequency contents) can be replaced with the non- overlapping region of $R_2{*}O$ as shown in Fig. 2(b). It is based on the fact that the spatial modulation frequencies of the reference waves can be located in the diagonal axes in the spatial frequency domain and most of the overlapping region between the DC term and object wave term is placed in one quadrant of spatial frequency contents of the object wave.

Practically, the replacement of the overlapping region can be performed while multiplying each reconstruction wave (R_1 and R_2) to its band-pass filtered frequency contents ($R_1{*}O$ and $R_2{*}O$). In the procedure, two object waves can be obtained using two reference waves and they should be theoretically the same, but slightly different from each other because of the different overlapping regions. From these two object waves, then, the spatial frequency components of one object wave in the overlapping region are replaced with those of the other object wave in the non-overlapping region as shown in Fig. 2(b). The spatial frequency components of the objective wave between $R_1{*}O$ and $R_2{*}O$ are the same because the object wave is the same. The spatial frequency distribution should be considered from the center of the filtered region ($R_1{*}O$ and $R_2{*}O$) and the overlapping region of $R_1{*}O$ can be replaced with the non-overlapping region of $R_2{*}O$ because they have the same spatial frequency distributions. In most cases, this method can provide better amplitude and phase information because the overlapping region is located at one quadrant of spatial frequency contents of the object wave except for the small spatial modulation of the reference wave or a high stiff object which has high spatial frequency components. Even in spite of the worst cases, this method can reduce the overlapping errors more than other methods. Consequently, the use of another reference wave in off-axis DH can make the second hologram which can give an additional object wave to replace the overlapping region between the DC term and the object wave term in the first hologram with non-overlapping region in the spatial frequency domain in the second hologram.

After obtaining the exact object wave in the hologram plane using this new filtering method, the wave propagates from the hologram plane to the object plane numerically based on scalar diffraction theory. By employing the Fresnel approximation, the reconstructed object wave (ψ_O) can be calculated from the object wave (ψ_H) in the hologram plane as

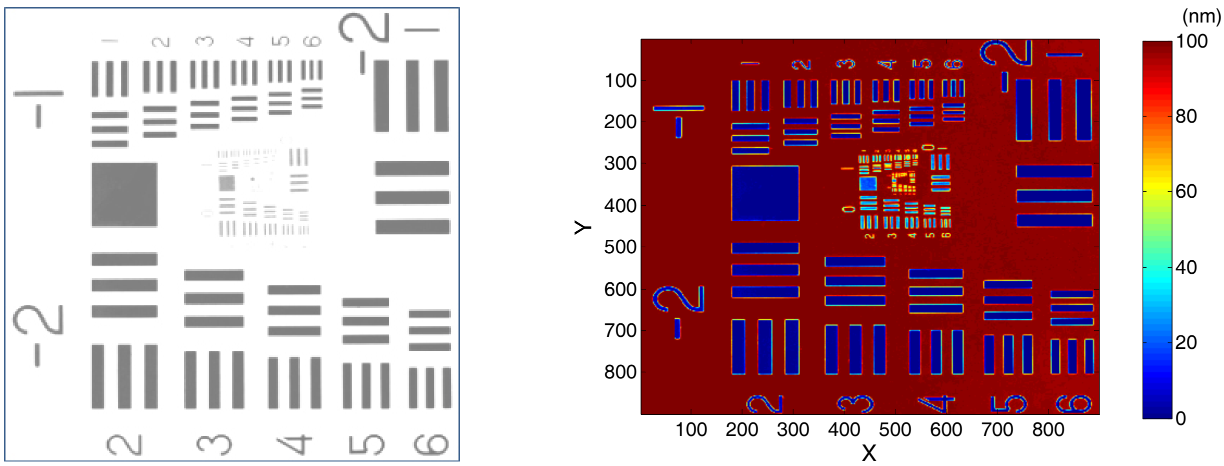
$$\psi_O = \frac{A\exp(i2\pi d/\lambda)}{i\lambda d}\exp\left[\frac{i\pi}{\lambda d}\left(x_O^{\ 2}+y_O^{\ 2}\right)\right] \times F\left\{\psi_H \exp\left[\frac{i\pi}{\lambda d}\left(x_H^{\ 2}+y_H^{\ 2}\right)\right]\right\} \tag{2}$$

where l is the wavelength and d is the distance between the hologram plane and the object plane. (x_O, y_O) and (x_H, y_H) mean the two dimensional coordinates of the object plane and the hologram plane, respectively. $F\{\}$ denotes a 2-D Fourier transform in the spatial domain. A is an arbitrary number, determined by the amplitudes of the reference wave or the reconstruction wave. From the resultant wave (ψ_O), the amplitude and phase images of the object can be decomposed and finally 3D surface height map is obtained from the phase image.

III. SIMULATION AND COMPARISON

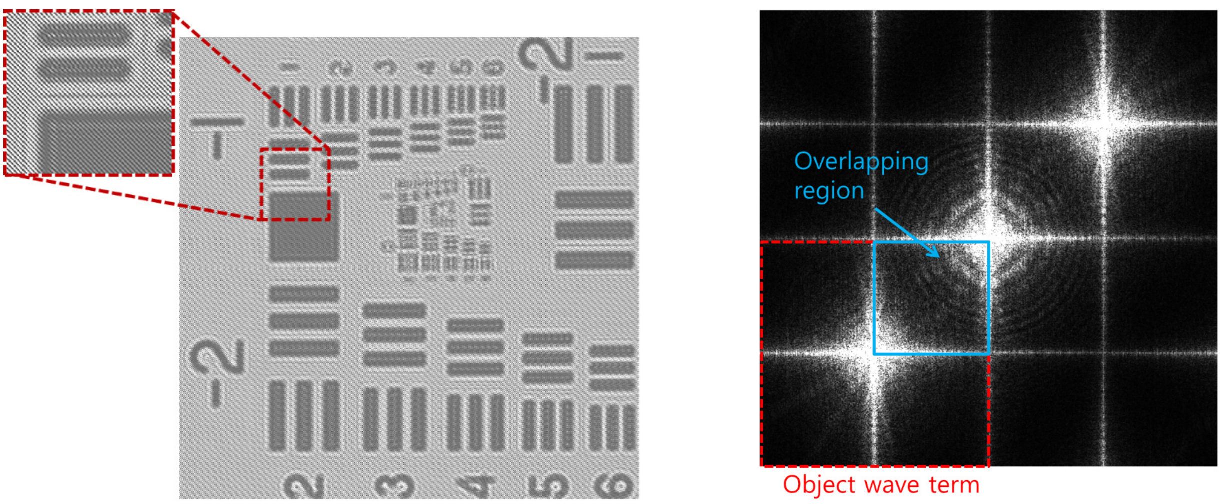
In order to validate the effectiveness of the new method, a simulation was performed with the new filtering technique compared to the conventional spatial filtering technique based on band-pass filtering [9]. For generating the digital hologram, a USAF 1951 test target image (899´899) was used as shown in Fig. 3. For the image and phase reconstruction, the height map of the target was set to be 100 nm at maximum based on the image to avoid the ambiguity problem. Figures 3(a) and 3(b) show the 2D intensity image and the 3D height map of the target, respectively. In this simulation, the distance between the object plane and the hologram plane was set as 20 mm and the pixel size of the hologram was assumed as 10 μm. The wavelength of the source was 635 nm.

In the conventional off-axis DH simulation, only one reference wave was used for the interference and the digital hologram could be generated based on the numerical propagation as shown in Fig. 4(a). In the hologram, the interference term was spatially modulated with the vertically and horizontally 0.9 ° tilted reference wave assumed as a plane wave. Then, the digital hologram could decompose a DC term, the object wave and its conjugate term in spatial frequency domain obtained from a 2D Fourier transform as shown in Fig. 4(b). The red dot rectangle in Fig. 4(b) means the quadrant including the object wave and the blue solid rectangle shows the overlapping region between the DC term and the object wave term. In order to extract the object wave from the hologram, the quadrant including the object wave term was only band-pass filtered and the reconstruction wave the same as the reference wave was



(a) (b)

FIG. 3. (a) The USAF 1951 test target image and (b) 3D height map assumed by 100 nm maximum height for the simulation.



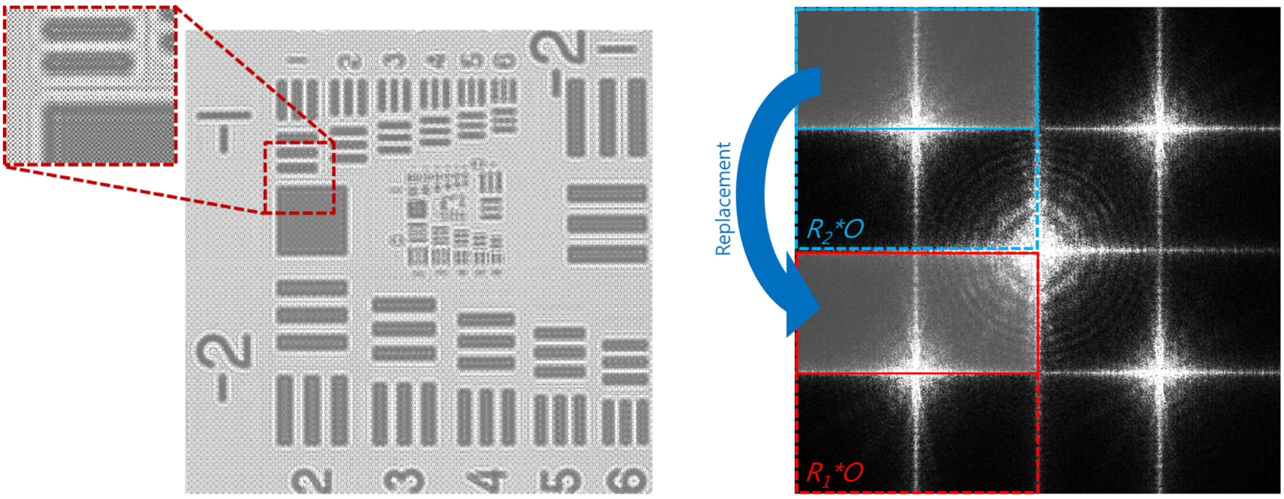
(a) (b)

FIG. 4. (a) Simulated hologram where the inlet shows the interference pattern from the tilted reference wave and (b) the spatial frequency contents of (a) in the conventional off-axis DH.

applied to the filtered term to remove the spatial modulation frequency. As shown in Fig. 6(a), however, the DC term was included in the filtered region and it deteriorated the reconstructed object wave. Further band-pass filtering can be applied to this spectrum to remove the DC term but, as previously explained, it limits the available spectrum of the object wave and often requires manual adjustment for selecting the desired order.

On the other hand, the image obtained from the new method contains two holograms, which mean two distinguishable interference patterns by different spatial modulation directions with two reference waves of R_1 (vertical and horizontal 0.9° tilted reference wave) and R_2 (vertical 0.9° and horizontal -0.9° tilted reference wave) as shown in Fig. 5(a). In the spatial frequency domain, two object wave terms (R_1*O and R_2*O) and their conjugate terms (R_1O* and R_2O*) appeared as seen in Fig. 5(b). The red dot rectangle indicates the quadrant including the object wave with the first reference wave (R_1*O) and the blue dot rectangle indicates the quadrant including the object wave with the second reference wave (R_2*O). Then, using two object wave spectrums, the region including the DC term of the red solid rectangle (upper portion) in R_1*O was replaced with the blue solid rectangle (upper portion) in R_2*O, which did not include the DC term. Because the DC term was eliminated with this procedure, the resultant spatial spectrum of the object wave was not affected by the DC term as shown in Fig 6(b).

Figures 7(a) and 7(b) show the reconstructed target amplitude image and 3D height map, respectively, after applying the numerical wave propagation. In order to avoid the diffraction noise from the edge, the apodization technique [13] was applied to the object wave as seen in Fig. 7(a). It was verified that the proposed method could reconstruct the 3D target successfully without any effort to adjust the band pass filter manually. Moreover, this new



(a) (b)

FIG. 5. (a) Simulated hologram where the inlet shows the interference patterns from two tilted reference wave and (b) the spatial frequency contents of (a) in the new off-axis DH. The overlapping region is replaced with the non-overlapping region.

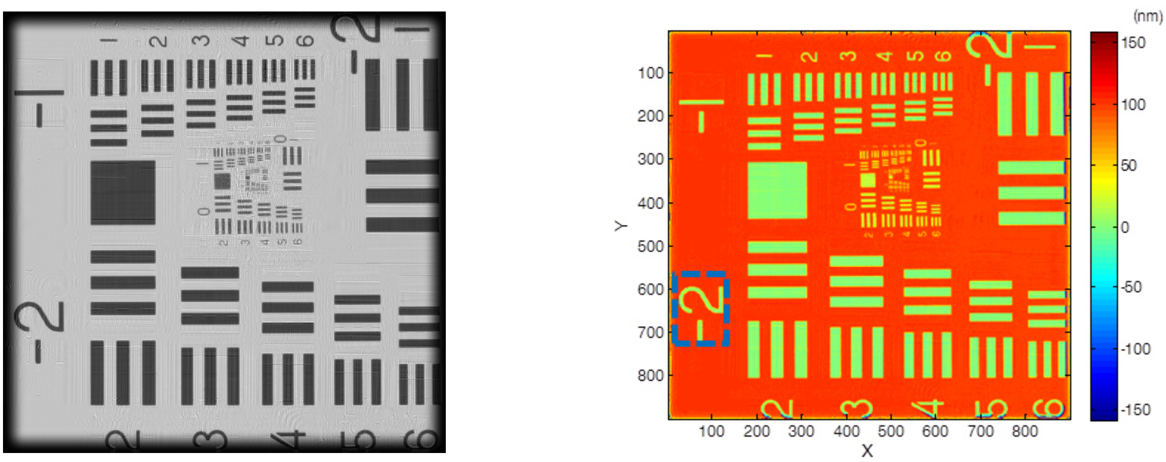
(a) (b)

FIG. 6. Spatial frequency contents of the object wave using the conventional band pass filtering method and (b) new method with the replacement.

method could provide better quality to the reconstructed 3D object compared to the previous method. Because of the remaining DC term in the spatial frequency contents of the object wave, the object wave reconstructed by the conventional method has high frequency noise in the image and phase. However, the object wave reconstructed by this new method contains less or no high frequency noise in its results. Figure 8 shows an example of the comparison of the enlarged 3D height maps ("-2" region of the target) between the conventional and the new methods. As shown in Figs. 8(a) and 8(b), the result of the new method has no noise caused by the DC term opposed to the result by the conventional method. Furthermore, in order to evaluate the performance of this new method, the root mean square (RMS) value of the difference between the reconstructed height map and the original height map was calculated and compared with the result of the conventional method. For this evaluation, the amplitude ratio between the reference and object waves varied from 0.1 to 5 in both methods and the amplitude of each reference wave in the new method was set as half the object wave amplitude, similar to the practical situations.

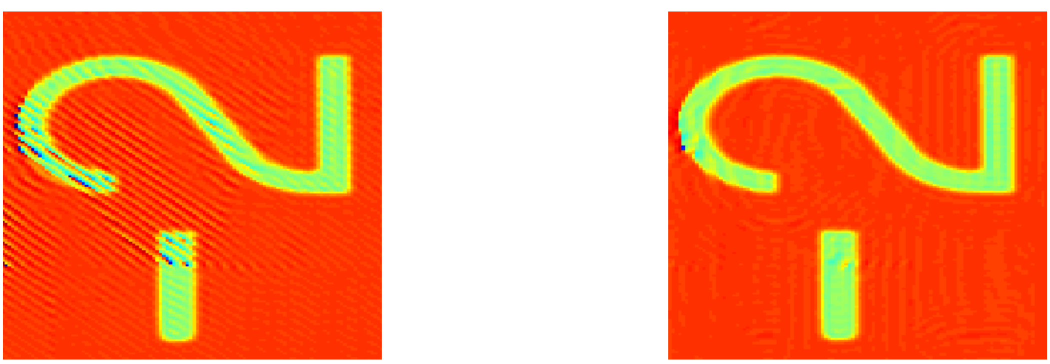
Figure 9 shows the RMS values of the height map differences in both cases. As shown in Fig. 9, the proposed method could extract the object wave from the hologram better than the conventional method. Specifically, the RMS values were 3.76 nm in the new method, better than 6.92 nm in the conventional method when the amplitude ratio (|R|/|O|) was 1. While the RMS values varied according to the amplitude ratio change in the conventional method, the performance of the new method was almost independent of the amplitude ratio. As the amplitude ratio increased, the height map difference of the conventional method decreased because of the relatively small object wave, of which intensity ($|O|^2$) is the dominant factor of the overlapping region. As previously mentioned, however, it may cause other noise issues because of the small object wave intensity. On the other hand, this overlapping region can be eliminated in the new method and then the object wave can be reconstructed free from the DC term.

In order to apply the proposed method, the two reference waves should be tilted diagonally. If the spectra of the reference waves are located vertically and horizontally, this method is difficult to apply because of the limitation of



(a) (b)

FIG. 7. (a) Reconstructed image of the USAF target and (b) reconstructed 3D height map by the proposed method.



(a) (b)

FIG. 8. Enlarged 3D height maps in the "-2" region of the target from (a) conventional method and (b) new method.

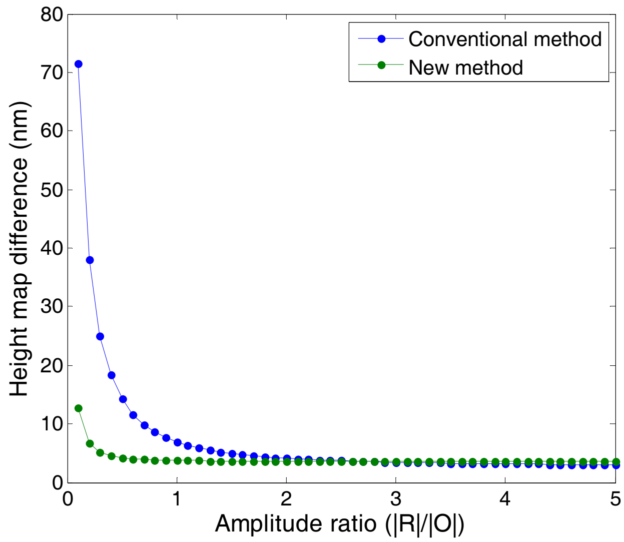


FIG. 9. Height difference between the reconstructed and original height maps.

the replacement with non-overlapping region. Moreover, the spatial filtering also has limitations because the zero-order spectrum (dc term) has large pure vertical and horizontal spectra. In typical off-axis digital holography, therefore, the diagonal spectrum is used to increase the spatial resolution of the image.

IV. CONCLUSION

In this investigation, a new method for spatial filtering in digital holography was proposed and verified with simulation work. To summarize, the new method is based on the simultaneous acquisition of two digital holograms, which can be separated by their distinct spatial modulation, in a single image. It is caused by two reference waves, which have different spatial modulation frequencies. Then, the overlapping region between the DC term and the object wave in the first hologram can be replaced with non-overlapping region of the object wave in the second hologram because the image contains two holograms where the same objective wave is recorded. In the simulation results, it was confirmed that the reconstructed image by the new method has better quality than the conventional method.

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