High-speed phase imaging by parallel phase-shifting digital holography

Takashi Kakue,[1] Ryosuke Yonesaka,[1] Tatsuki Tahara,[1] Yasuhiro Awatsuji,[1,*] Kenzo Nishio,[2] Shogo Ura,[1] Toshihiro Kubota,[3] and Osamu Matoba[4]

[1]*Graduate School of Science and Technology, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606-8585, Japan*

[2]*Advanced Technology Centre, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606-8585, Japan*

[3]*Kubota Holography Laboratory Corporation, Nishihata 34-1-609, Ogura-cho, Uji 611-0042, Japan*

[4]*Graduate School of System Informatics, Kobe University, Rokkodai 1-1, Nada-ku, Kobe 657-8501, Japan*

**Corresponding author: awatsuji@kit.ac.jp*

Received July 13, 2011; revised September 23, 2011; accepted September 23, 2011; posted September 26, 2011 (Doc. ID 151034); published October 19, 2011

Parallel phase-shifting digital holography can obtain three-dimensional information of a dynamically moving object with high accuracy by using space-division multiplexing of multiple holograms required for phase-shifting interferometry. We demonstrated high-speed parallel phase-shifting digital holography and obtained images of the phase variation of air caused by a compressed gas flow sprayed from a nozzle. In particular, we found the interesting phenomenon of periodic phase distributions. Reconstructed images were obtained at frame rates of 20,000 and 180,000 frames per second. © 2011 Optical Society of America

OCIS codes: 090.1995, 120.5050, 090.1760, 110.1758.

Digital holography [1,2] is promising technique for phase and three-dimensional (3D) measurement, and has been actively researched in recent years [3–11]. The technique digitally records holograms using an image sensor such as a charge-coupled device or complementary metal oxide semiconductor sensor and reconstructs 3D information by computer. In particular, in-line digital holography has been actively investigated because of the low resolution of an image sensor and the simplicity of a constructed optical setup. However, in in-line digital holography, unwanted images, such as the zeroth-order diffraction image and the conjugate image, are superimposed on the image of an object (the desired image) in principle because the reference wave is orthogonally introduced onto the image sensor. Although off-axis digital holography can reconstruct only the desired image by applying spatial filtering [12], the field of view and the measurement range are narrowed in off-axis digital holography due to the spatial resolution of typical image sensors.

Phase-shifting digital holography [13] is an attractive technique that can solve the problems experienced with in-line digital holography. This technique can eliminate unwanted images and make it possible to acquire clear images and measure objects with a high degree of accuracy because the technique applies phase-shifting interferometry to digital holography. However, it requires the recording of at least two holograms. Therefore, it is quite difficult for phase-shifting digital holography to record or measure a dynamically moving object. We previously proposed parallel phase-shifting digital holography (PPSDH) [14–16], a technique that records a single image in which the multiple holograms required for phase-shifting interferometry are combined by space-division multiplexing. Because the technique can perform phase-shifting interferometry by single-shot recording, it is capable of 3D measurement of a dynamically moving object.

We reported the effectiveness of PPSDH and demonstrated a constructed system in previous publications [14–17]. Until now, however, high-speed phase-shifting digital holography has not been reported because a high-speed camera that can be applied to PPSDH had not yet been developed. In the present study, we aim to construct a high-speed PPSDH system by use of a high-speed polarization-imaging camera and to obtain 3D information of a dynamically moving object using the constructed system. In particular, because 3D information of an object is obtained from a phase image of the object and a phase distribution is helpful for estimation of the thickness and the refractive index of a transparent object, we aim at phase imaging.

Figure 1 shows the image reconstruction process of a hologram recorded by PPSDH. In phase-shifting interferometry, multiple phase-shifted interference fringe images are required; three, four, or more than four images are frequently employed in view of robustness against changes in environmental conditions. A system employing a parallel four-step phase-shifting method has already been developed [18]. In contrast, in PPSDH, as the number of phase shifts is reduced, the sampling interval of each phase-shifted hologram is narrowed. Therefore, the recordable space–bandwidth product of each phase-shifted hologram increases. As a result, the quality of the reconstructed images improves and the field of view increases [19]. Thus, in our study, we adopted parallel two-step phase-shifting digital holography [16,17] to achieve improved image quality. Parallel two-step phase-shifting digital holography records a

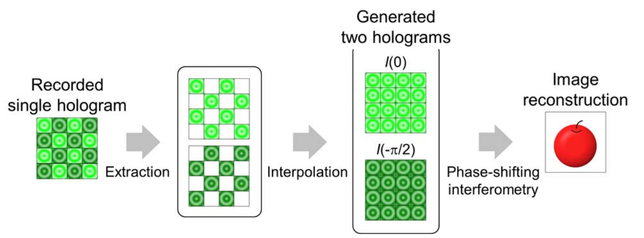

Fig. 1. (Color online) Schematic flow of image reconstruction of the hologram recorded by parallel two-step phase-shifting digital holography.

single image in which the information of two holograms required for two-step phase-shifting interferometry is combined by space-division multiplexing, as shown in Fig. 1. Pixels with each phase shift are extracted from the recorded image, and two images that have vacant pixels are obtained. Two phase-shifted holograms, $I(0)$ and $I(-\pi/2)$, are generated by interpolating the vacant pixels in the obtained images. We can calculate the complex amplitude distribution of an object wave by applying two-step phase-shifting interferometry [20] to the generated holograms.

Figure 2 shows a schematic diagram of an example of optical implementation of PPSDH. A perpendicularly polarized wave is emitted from the laser and is divided into two waves by the beam splitter. One serves as the reference wave. The other illuminates an object, and the wave refracted or diffracted by the object is the object wave. The reference wave is introduced into the quarter-wave plate, whose fast axis is inclined at an angle of 45° relative to the polarization direction of the original reference wave, as shown in Fig. 2, to convert the perpendicularly polarized light in the reference wave to circularly polarized light. In other words, the phase retardation of the reference wave in the slow-axis direction compared with that in the fast-axis direction is $\pi/2$. Interference fringes are formed on the image sensor plane by the object wave and the reference wave. The image sensor of the polarization-imaging camera has a pixel-by-pixel anisotropic polarization-detecting function. Each pixel of the polarization-detecting function corresponds to each pixel of the image sensor, and each phase-shifted reference wave can be selected with this function. Thus, a single image containing the multiplexed information of two holograms required for two-step phase-shifting interferometry can be obtained.

We constructed an experimental system based on the optical implementation shown in Fig. 2 and recorded 3D moving pictures of a dynamically moving object. We used a Nd:YVO_4 laser as a light source and a high-speed polarization-imaging camera (Photron FASTCAM-SA5-P; Photron Ltd.) as an image sensor. The wavelength of the light was 532 nm, and the pixel pitch of the high-speed camera was 20 μm. The camera selects four polarization axes for 2×2 pixels, but we used only two of the four axes for implementing two-step phase-shifting digital holography. We recorded the intensity of the reference wave, A_r, at the beginning of the hologram recording process since two-step phase-shifting interferometry requires not only $I(0)$ and $I(-\pi/2)$ but also A_r [20].

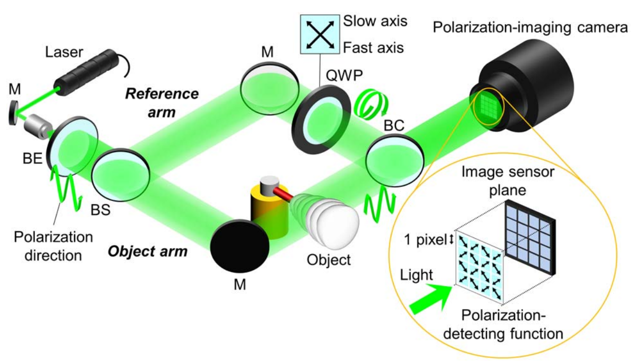

Fig. 2. (Color online) Schematic diagram of an example of the optical setup of parallel two-step phase-shifting digital holography.

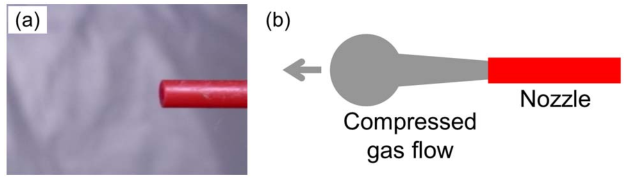

Fig. 3. (Color online) Object (compressed gas flow). (a) Photograph and (b) schematic diagram.

We used a compressed gas flow sprayed from a nozzle as an object in order to obtain high-speed phase images. Figure 3 shows a photograph and a schematic diagram of the object. The inner diameter of the nozzle was 1 mm. We recorded the phase change of air caused by the gas flow. First, we positioned two nozzles facing each other 19 cm away from the camera and sprayed compressed gas from the right nozzle.

We captured holograms at a frame rate of 20,000 frames per second (fps) when the number of the pixels in the holograms was 512×512. Figure 4 shows the phase images reconstructed from the recorded holograms. The pixel values in the phase images are normalized in the range from 0 to 255, where the pixel value of 255 is equivalent to a phase of 2π. The images in Fig. 4 were obtained at $t = 0$, 10, 15, 20, 65, 80, 85, 90, 95, and 100 ms [(a) to (j), respectively]. The heads of the two nozzles were reconstructed in the right and left parts in each image. The abrupt transitions from white to black in each image resulted from phase wrapping from 2π to 0. Clear phase variation images were obtained because the unwanted images, such as the zeroth-order diffraction image and the conjugate image, were eliminated by the use of phase-shifting interferometry. The dim circular rings superimposed on each image in Fig. 4 resulted from strain in the surface of the image sensor caused by stress that had occurred when the image sensor was packaged. First, we can observe that the phase gradually increased as the flow rate of the compressed gas increased. Next, the phase increased from the opposite side of the sprayed nozzle, as shown in Fig. 4(f). After that, the phase of the background changed by the gas which was reflected by the left nozzle. In addition, interesting periodic phase distributions appeared.

To obtain images of faster phase changes, we captured holograms at a frame rate of 180,000 fps when the number of the pixels in the holograms was 128×128. We positioned a single nozzle 20 cm away from the camera.

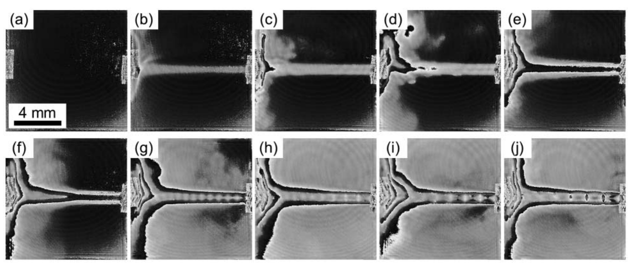

Fig. 4. Phase images reconstructed from the recorded holograms at a frame rate of 20,000 fps (Media 1). These images were obtained at $t = 0$, 10, 15, 20, 65, 80, 85, 90, 95, and 100 ms [(a) to (j), respectively].

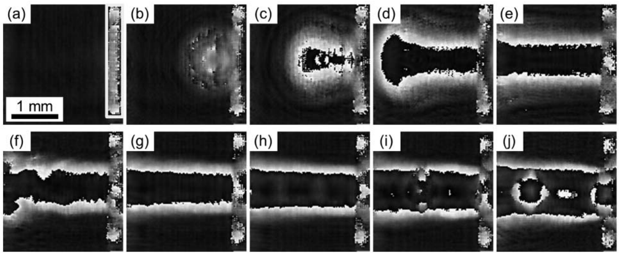

Fig. 5. Phase images reconstructed from the recorded holograms at a frame rate of 180,000 fps (Media 2). These images were obtained at $t = 0$, 3.2, 4.0, 4.8, 5.6, 24, 67, 87, 95, and 120 ms [(a) to (j), respectively].

Figure 5 shows the phase images reconstructed from the recorded holograms. The pixel values in the phase images are normalized in the range from 0 to 255, where the pixel value of 255 is equivalent to a phase of 2π. The images in Fig. 5 were obtained at $t = 0$, 3.2, 4.0, 4.8, 5.6, 24, 67, 87, 95, and 120 ms [(a) to (j), respectively]. The head of the nozzle was reconstructed at the right part in each image. The head is indicated by the light-blue framed rectangle in Fig. 5(a). Although the quality of the reconstructed images degraded due to the smaller number of pixels in the recorded holograms, we successfully obtained images of the phase variation. In Fig. 5, first, we can observe that the compressed gas was sprayed from the nozzle. The gas flow looked like a laminar one. Next, the flow looked like a turbulent one in Fig. 5(f). After that, the turbulentlike flow again became a laminarlike one, as shown in Fig. 5(g). Then, periodic phase distributions were also observed, as shown in Fig. 5(j).

In conclusion, we constructed a PPSDH system for high-speed 3D imaging. The constructed system can record a single hologram in which the information of two holograms required for two-step phase-shifting interferometry is spatially multiplexed with a single-shot exposure. By applying two-step phase-shifting interferometry, high-quality images in which unwanted images, such as the zeroth-order diffraction image and the conjugate image, are eliminated can be reconstructed from the recorded holograms. A compressed gas flow was sprayed from a nozzle, and the phase variation of air caused by the phenomenon was recorded by the constructed system. We reconstructed phase images of gas flow by using two-step phase-shifting digital holography. Intriguingly, periodic phase distributions were reconstructed by the system. In summary, we successfully demonstrated high-speed 3D imaging by employing PPSDH. The frame rate of 180,000 fps is, to our knowledge, the fastest yet achieved, not only in phase-shifting digital holography but also in phase-shifting interferometry and digital holography. It is expected that PPSDH will contribute to 3D measurement of dynamically moving objects, such as microparticles, fluid flow, mechanical vibrations, and living specimens.

T. Kakue and T. Tahara are Research Fellows of the Japan Society for the Promotion of Science (JSPS).

We thank Photron Ltd., particularly Mr. T. Onuma, for kindly providing the high-speed polarization-imaging camera. This study was partially supported by the Funding Program for Next Generation World-Leading Researchers through the JSPS, and by a JSPS Research Fellowship for Young Scientists.

References

1. J. W. Goodman and R. W. Lawrence, Appl. Phys. Lett. **11**, 77 (1967).
2. T.-C. Poon, J. Holography Speckle **1**, 6 (2004).
3. B. Javidi and E. Tajahuerce, Opt. Lett. **25**, 610 (2000).
4. B. Javidi, S. Yeom, I. Moon, and M. Daneshpanah, Opt. Express **14**, 3806 (2006).
5. T. Nomura, B. Javidi, E. Murata, S. Nitanai, and T. Numata, Opt. Lett. **32**, 481 (2007).
6. T. Nomura and B. Javidi, Opt. Lett. **32**, 2146 (2007).
7. P. Ferraro, S. Grilli, L. Miccio, D. Alfieri, S. D. Nicola, A. Finizio, and B. Javidi, J. Display Technol. **4**, 97 (2008).
8. C. P. McElhinney, B. M. Hennelly, and T. J. Naughton, Appl. Opt. **47**, D71 (2008).
9. M. Kempkes, E. Darakis, T. Khanam, A. Rajendran, V. Kariwala, M. Mazzotti, T. J. Naughton, and A. K. Asundi, Opt. Express **17**, 2938 (2009).
10. L. Martínez-León, M. Araiza-E, B. Javidi, P. Andrés, V. Climent, J. Lancis, and E. Tajahuerce, Opt. Express **17**, 12900 (2009).
11. S. Murata, D. Harada, and Y. Tanaka, Jpn. J. Appl. Phys. **48**, 09LB01 (2009).
12. E. Cuche, P. Marquet, and C. Depeursinge, Appl. Opt. **39**, 4070 (2000).
13. I. Yamaguchi and T. Zhang, Opt. Lett. **22**, 1268 (1997).
14. M. Sasada, Y. Awatsuji, and T. Kubota, in *Technical Digest of the 2004 ICO International Conference: Optics and Photonics in Technology Frontier* (International Commission for Optics, 2004), pp. 187–188.
15. Y. Awatsuji, M. Sasada, and T. Kubota, Appl. Phys. Lett. **85**, 1069 (2004).
16. Y. Awatsuji, T. Tahara, A. Kaneko, T. Koyama, K. Nishio, S. Ura, T. Kubota, and O. Matoba, Appl. Opt. **47**, D183 (2008).
17. T. Tahara, K. Ito, M. Fujii, T. Kakue, Y. Shimozato, Y. Awatsuji, K. Nishio, S. Ura, T. Kubota, and O. Matoba, Opt. Express **18**, 18975 (2010).
18. J. Millerd, N. Brock, J. Hayes, M. North-Morris, M. Novak, and J. Wyant, Proc. SPIE **5531**, 304 (2004).
19. T. Tahara, Y. Awatsuji, K. Nishio, S. Ura, T. Kubota, and O. Matoba, Opt. Rev. **17**, 519 (2010).
20. X. F. Meng, L. Z. Cai, X. F. Xu, X. L. Yang, X. X. Shen, G. Y. Dong, and Y. R. Wang, Opt. Lett. **31**, 1414 (2006).