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Motoharu Fujigaki
Hiroki Minamino
Yorinobu Murata

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Motoharu Fujigaki,[a,*] Hiroki Minamino,[b] and Yorinobu Murata[c]
[a]University of Fukui, Graduate School of Engineering, Department of Human and Artificial Intelligent Systems, Fukui, Japan
[b]Wakayama University, Graduate School of Systems Engineering (former), Wakayama, Japan
[c]Wakayama University, Faculty of Systems Engineering, Wakayama, Japan

Abstract. Recently, it has become necessary to detect cracks in structures such as buildings and bridges. Phase-shifting digital holography is one valuable method that can be used to measure the strain distribution on the surface of an object. However, to simplify the optical measurement setup, more compact equipment is required. An interferometric trigger method with dual piezo actuators for phase shifting is proposed. This method is useful for designing a head discrete-type measurement system that uses phase-shifting digital holography with multiple imaging sensors. The ability to phase shift using the proposed trigger method was confirmed with the reconstruction of an object and an experiment that was performed to measure the displacement distribution. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.57.11.114105]

1 Introduction

Recently, it has become necessary to detect cracks in structures such as buildings and bridges. The strain distribution at a target area provides information about the presence of cracks. Therefore, it is necessary to develop a compact strain distribution measurement device for field measurements.

Phase-shifting digital holography[1,2] is one of the valuable methods used to measure the strain distribution on the surface of an object. Phase-shifting digital holographic interferometry (DHI) has been applied for noncontact measurements of shape and deformation distributions.[3,4] Many researchers have studied this method. Several types of compact instruments have been developed,[3,5–9] and several types of phase-shifting methods have been proposed.[10–12] The authors have also developed compact instruments for strain distribution measurements.[13,14] In conventional methods, several object waves are required to measure the in-plane displacement and strain distributions.

However, the authors have been studying an optical system and a calibration method that uses multiple imaging sensors via phase-shifting digital holography.[15,16] A method for generating reference waves with phase shifting using a flat glass plate has also been proposed.[17] The biggest advantage of the proposed methods is the reduction of the number of object waves. This results in a compact and handheld head for measuring the strain distribution. Using this result, authors have a plan to develop a compact head discrete-type measurement system that uses phase-shifting digital holography with multiple imaging sensors as shown in Fig. 1. The camera head shown in Fig. 1 has the minimum optical setup for shifting phase and imaging devices inside.

In general, a piezoelectric transducer (PZT) stage with feedback control to eliminate any hysteresis effect is used as a phase-shifting device. However, a PZT stage with feedback is not suitable as a compact head discrete-type measurement system because of its size. However, authors have proposed an interferometric trigger method that uses a small PZT to overcome the influence of the hysteresis effect.[18] However, it is difficult to structurally apply this method for generating the reference waves mentioned above. It is necessary to develop a phase-shifting mechanism that utilizes a small device, such as a small PZT.

Therefore, in this paper, an interferometric trigger method with dual PZTs for DHI is proposed. The light source is separated into two parts. One is used for DHI. The other source is used for generating the trigger signal. The compact head discrete-type measurement system as shown in Fig. 1 will be realized using the proposed method. An optical setup for the proposed method was constructed. The usefulness of the proposed method was experimentally confirmed by reconstruction of an object and the successful measurement of its displacement distribution.

2 Interferometric Trigger Method with Dual PZTs

The proposed optical system is shown in Fig. 2. The collimated light was divided into two beams, which were used in the measurement section and for generating the trigger.

In the measurement section, an interferometer of the digital holography was composed of a half mirror (HM3) and a mirror (M3). An object beam and a reference beam were interfered by the imaging sensor, and the interfered pattern was taken by an imaging sensor as a digital hologram. Mirror M3 was attached on the PZT (P2) used as the phase-shifting device. The given signal to P2 is in the form of triangle waves generated by a function generator. The imaging sensor takes phase-shifted digital holograms. However, the phase-shifting amount was unknown because of the influence of the hysteresis effect of the PZT.

However, in the generating trigger section, a Twyman–Green interferometer was composed of a half mirror (HM2),
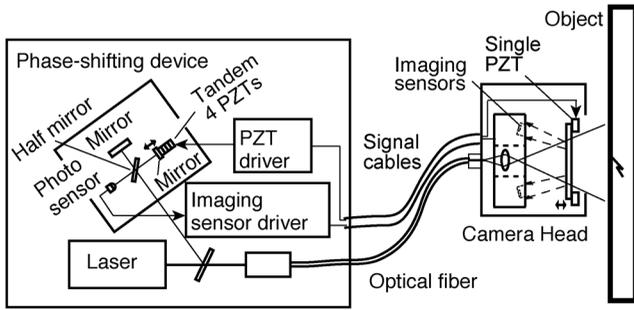
**Fig. 1** Framework of a compact head discrete-type measurement system.
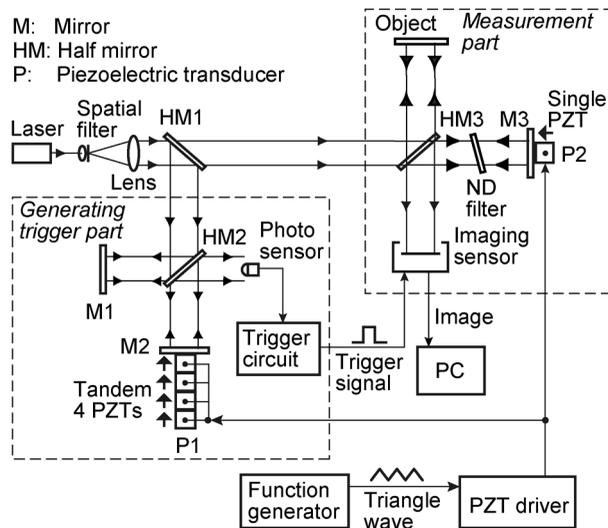
Fig. 2 Optical system setup.

mirror M1, and mirror M2. Mirror M1 was attached on a set of four tandem PZTs (P1) that were used as the phase-shifting device. A fringe pattern interfered the two beams from mirror M1, and M2 appeared around a photosensor. A phototransistor was used as the photosensor. The phase of the fringe pattern shifted, which corresponded to the displacement of mirror M2.

Figure 3 shows the timing charts of elongation of P1 and P2, the trigger signal, and the exposure time for the interferometric trigger method with the dual PZT. Here, λ represents the wavelength of the light source. The characteristics of all PZTs used in the proposed optical system were assumed to be identical. The electrodes in each PZT that were in P1 were connected in parallel. The signal supplied to P1 was the same triangular wave supplied to P2. Therefore, the elongation of each PZT that was in P1 was expected to be the same as the elongation of P2. Thus, the total displacement of mirror M2 was expected to be four times larger than the displacement of mirror M3, as shown in Fig. 3(a). That is, the phase-shifting speed of a fringe pattern generated by M2 was expected to be four times faster than the phase-shifting speed of a fringe pattern generated by M3.

Figure 3(b) shows the phases of the reference wave and the trigger wave that correspond to the elongations of P1 and P2, respectively. The trigger wave period was 1/4 that of the reference wave. Figure 3(c) shows the intensity of the trigger
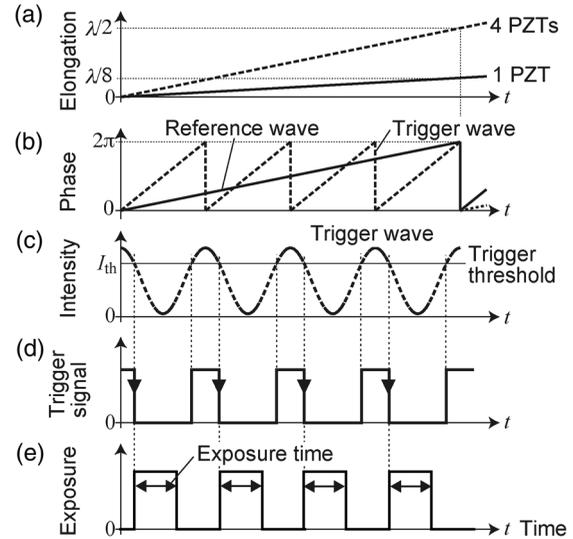
Fig. 3 Principle of the interferometric trigger method with dual PZTs: (a) PZT elongation, (b) phases of the reference and trigger waves, (c) intensity of the trigger wave, (d) trigger signal, and (e) exposure time.

wave. Here, I_{th} is the trigger threshold. Figure 3(d) shows the trigger signal generated upon binarizing the trigger wave with the trigger threshold I_{th}. Figure 3(e) shows the exposure time of the imaging sensor. The exposure beginning time is the falling edge of the trigger signal in this explanation. The time span for exposure was set up on the imaging sensor in advance. The digital hologram recorded by the imaging sensor was produced as the integral value of the intensity of the hologram during the exposure time. The continuous signal gives no effect for the reconstructed phase and it affects nothing to the final measurement accuracy. The phase at the middle time during the exposure time was obtained using the phase-shifting method.

3 Experiment to Evaluate the Performance of the Imaging Sensor

3.1 Reconstruction of an Object

First, the utility of the proposed method was confirmed with an experiment to reconstruct an object using phase-shifting digital holography. Figure 4 shows the experimental optical setup. A He-Ne laser with an output of 8 mW and a wavelength of 632.8 nm was used as the light source. The grabbed image size was 960×960 pixels. The imaging pixel pitch was $3.75 \, \mu$m. Figure 5 shows the four tandem PZTs and the attached mirror that was used as the phase-shifting device. The icosahedral dice shown in Fig. 6 was used as the object. The distance of the object from the image sensor was 240 mm.

A periodic triangular wave with a frequency of 0.3 Hz was applied to both the single PZT and the four tandem PZTs. The trigger signals were generated by an interferometer with the four tandem PZTs. The imaging sensor recorded four phase-shifted digital holograms according to the trigger signals, as previously described.

The set of the four phase-shifted digital holograms is shown in Fig. 7. The reconstructed image is shown in Fig. 8. The icosahedral dice was clearly reconstructed without any
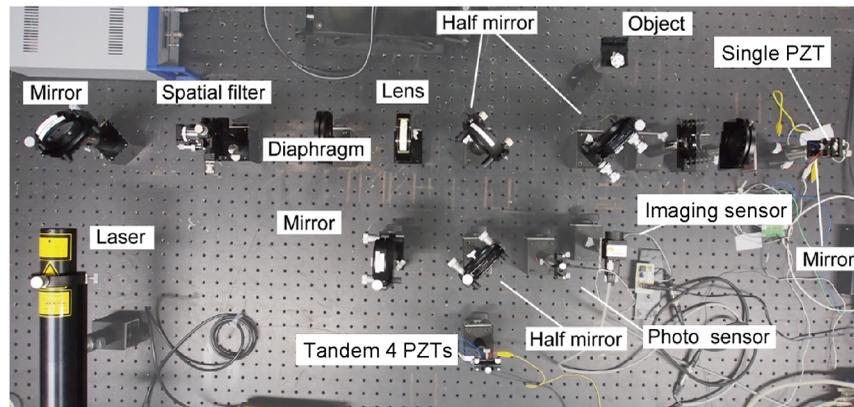
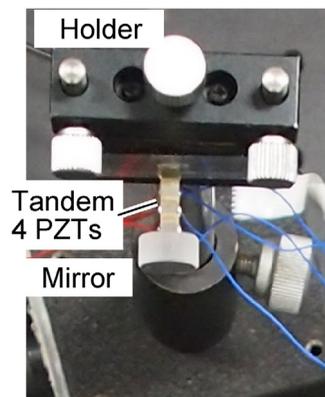**Fig. 4** Photograph of the optical setup for the reconstruction experiment.

Fig. 5 Photograph of the four tandem PZTs.

Fig. 6 Photograph of the object (icosahedral dice).

Fig. 7 Phase-shifted digital holograms.

Fig. 8 Reconstructed image.

zero-order reconstructed components visible in the center of the reconstructed image. This result demonstrates the feasibility of the proposed interferometric trigger method with dual PZTs.

3.2 Displacement Distribution Measurement

The utility of the proposed method was confirmed via an experiment to measure the displacement of a cantilever using phase-shifting digital holography. Figure 9 shows the optical experimental setup. The cantilever shown in Fig. 10, which was 25 mm long, was used as the measurement specimen. The surface of the specimen was painted with white lacquer. The reconstructed length of the specimen was 300 mm.

A PZT actuator was located behind the cantilever to apply displacement in the z-direction to the cantilever. The contact point with the cantilever was 20 mm from the edge of the fixed part. The PZT actuator applied 1.00, 3.00, and 5.00 μm of displacement at the point.

The phase-shifted digital holograms were recorded by an imaging sensor using the proposed method. The phase difference was obtained from the reconstructed images before and after displacement. The speckle noise was reduced with a windowed DHI[19,20] with 256 divided windows in this experiment. Figures 11(a)–11(c) show the phase differences when the PZT actuator applied 1.00, 3.00, and 5.00 μm of displacement at the contact point, respectively.

The displacement distributions of the cantilever were obtained by unwrapping the phase differences and multiplying the unwrapped phase by $\lambda/(4\pi)$. The displacement
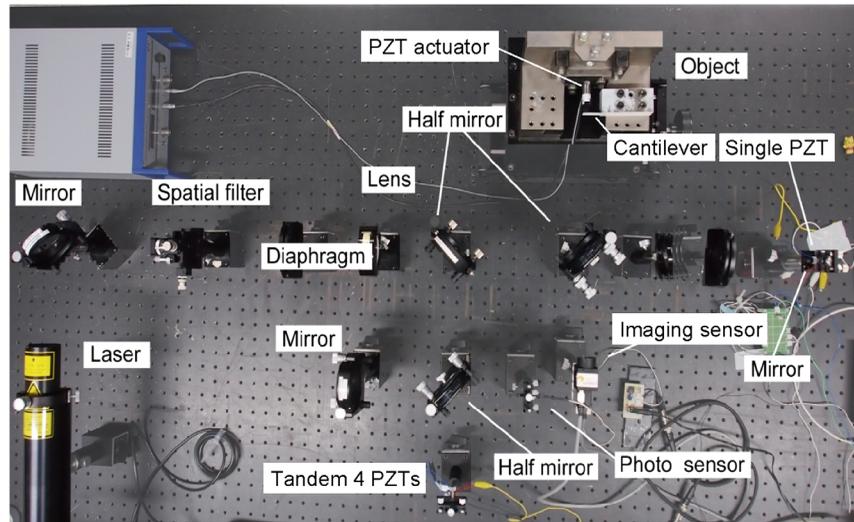
Fig. 9 Photograph of the optical setup for the displacement measurement experiment.
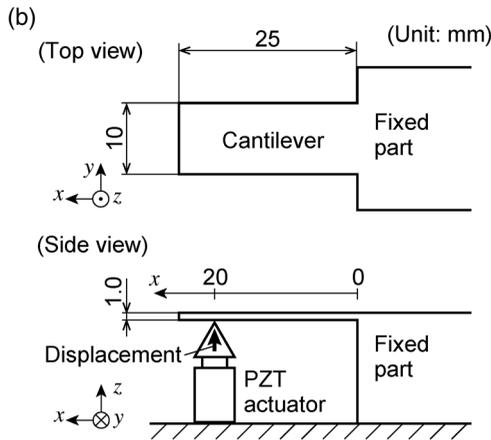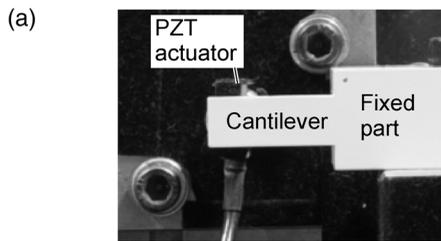
(a)

(b)

Fig. 10 Specimen for the displacement measurement: (a) photograph and (b) schematic diagram.

distribution along the horizontal center line in Figs. 11(a)–11(c) is shown in Fig. 12.

From this result, the displacement of the cantilever was measured by the imaging device using the proposed method and the optical setup as shown in Fig. 9. Table 1 shows the measured displacements and the difference between the given and measured displacements at the specific displacement point ($x = 20.0$ mm). This result shows
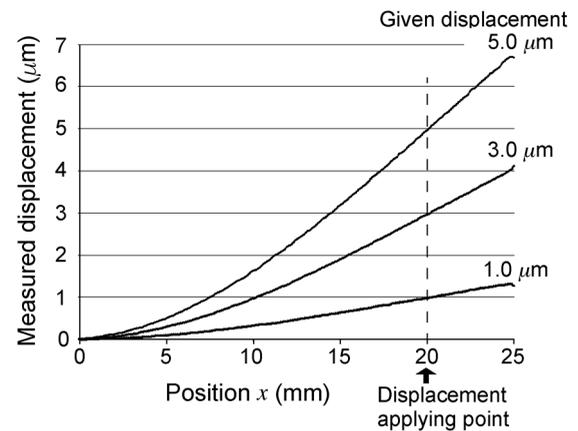

Fig. 12 Displacement distribution along the horizontally centered line in Fig. 11.
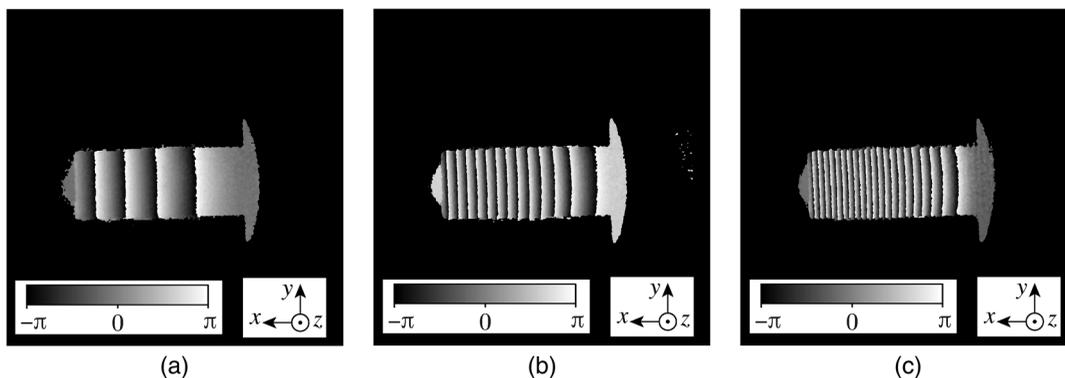

Fig. 11 Phase difference: (a) 1.00 μm, (b) 3.00 μm, and (c) 5.00 μm.

Table 1 Measured displacements and difference at the applied displacement point ($x = 20.0$ mm).

Given displacement	Measured displacement	Difference (unit: μm)
1.00	0.99	0.01
3.00	2.97	0.03
5.00	4.96	0.04

that the difference was not significant. The linearity of the PZT actuator was 0.15% of the stroke according to the specification. The value was 0.023 μm because the stroke was 15 μm. The differences in this result were also not large compared with this value.

4 Conclusions

A phase-shifting mechanism using the interferometric trigger method with dual PZTs was proposed. First, the utility of the proposed method was confirmed in an experiment designed to reconstruct an object using phase-shifting digital holography. Second, the proposed method was used to measure the out-of-plane displacement distribution of a cantilever using phase-shifting digital holography. The proposed method successfully measured the displacement distribution.

Compact equipment for displacement and strain distribution measurements can be realized using the proposed method. This method is also useful for designing a head discrete-type measurement system that involves phase-shifting digital holography with multiple imaging sensors as shown in Fig. 1.

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Motoharu Fujigaki is a professor at the University of Fukui. He received his BS and MS degrees in mechanical engineering from Osaka University in 1990 and 1992, respectively, and he received his PhD in 3-D shape measurements from Osaka University in 2001. He transferred from Wakayama University to University of Fukui in 2015. He is interested in optical metrology using image processing, especially 3-D shape and deformation measurements using phase analysis methods and small displacement measurements using laser interferometry. He is also interested in applying optical methods to other practical fields, such as robotics, civil engineering, and space engineering. He is a member of JSEM, SEM, SPIE, OSA, and ASEM, among other organizations.

Hiroki Minamino is a former graduate student of Wakayama University. He received his BS degree in opto-mechatronics and MS degree in systems engineering from Wakayama University in 2013 and 2015, respectively. He had studied a displacement and strain measurement method using a phase-shifting digital holography in Wakayama Univeristy.

Yorinobu Murata is a professor at the Wakayama University. He received his BS and MS degrees in polymer materials engineering and his PhD in materials science and energy engineering from Yamagata University, Japan, in 1991, 1993, and 1996, respectively. He was a visiting researcher at the Smart Material Structures Research Center of the University of Maryland from 1999 to 2000. His research interests are in advanced polymer ultrasonic transducers, acoustoelastic stress measurements, and nondestructive testing by ultrasonic imaging.