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A method of generating reference wave in interferometric measurement with multiple imaging sensors

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ABSTRACT

Phase-shifting digital holography is a convenient method to measure small 3D displacement distributions on the surface of an object. More than three independent sensitivity vectors are theoretically necessary to obtain a 3D displacement. In general, three incident waves are used to obtain three sensitivity vectors. However, the optical system becomes complicated. Therefore, to simplify the optical system, authors have developed a method to use multiple imaging sensors instead of using multiple incident waves. In this paper, a method of generating reference waves using a flat glass plate and multiple imaging sensors for interferometric measurement was proposed. The calibration method and the calculation method to obtain 3D displacement using multiple imaging sensors were also proposed. The evaluation was performed by measuring the displacement of a flat plate moved with a 3-axis PZT stage using phase-shifting digital holography. The results showed that the proposed method was effective.

1. Introduction

The development of compact and conventional strain distribution measurement equipment for practical use is required to monitor the health and life-lengthening characteristics of infrastructures such as steel bridges. Phase-shifting digital holography is a convenient method to measure the 3D displacement and strain distributions on the surface of an object [1]. Many researchers have developed several compact devices [2–8]. Some authors have also developed compact devices for strain distribution measurements [9,10].

More than three independent sensitivity vectors are theoretically necessary to obtain a 3D displacement. In general, three incident waves are used to obtain three sensitivity vectors [10]. The optical system, however, becomes complicated. Three light sources or an optical system to divide a wave into three waves are necessary. Each wave is divided into a reference wave and an incident wave. A composite reference wave is generated with mixing the three reference waves using several half prisms. Consequently, a lot of optical devices are necessary.

Therefore, previously authors have proposed a method to use multiple imaging sensors instead of multiple incident waves to simplify the optical system [11–12]. Authors also have proposed a calibration method for strain measurement using multiple cameras and digital holography [13]. These were feasibility studies to confirm that a compact device for strain distribution measurements could be produced using multiple imaging sensors. The benefit to use more than three imaging sensors was to reduce random noises because of the average effect. However, in these studies, the optical system for producing a reference wave was still complicated.

A mechanism to supply a reference wave with a shifting phase to each imaging sensor with a small number of optical devices is required to realize compact equipment for strain distribution measurements using multiple cameras. In this paper, a method of generating reference waves using a flat glass plate for interferometric measurement is proposed. The phase of the reference wave can easily be shifted. The calibration method and the calculation method to obtain the 3D displacement using multiple imaging sensors are also proposed. The evaluation is performed by measuring the displacement of a flat plate moved with a 3-axis PZT stage using phase-shifting digital holography.

2. Principle of 3D displacement measurement with multiple imaging sensors

The displacement vector at a point is calculated from phase difference between measurements taken before and after the object is moved. Fig. 1 shows a positional relationship between a light source, imaging sensors and sensitivity vectors. The angle between an incident wave onto an object and the scattered waves in the direction of the image sensor i is shown as θ_i in this figure. The direction of the sensitivity vector $\boldsymbol{e}_i$ is the direction of the angle that bisects the angle θ_i. The vector $\boldsymbol{d}$ is the displacement vector at the point P, as shown in Fig. 1, when a point P on

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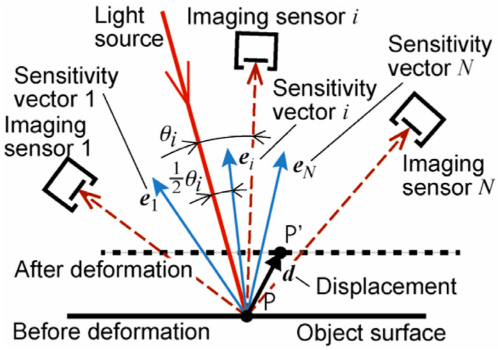

Fig. 1. Positional relationship between a light source, imaging devices and sensitivity vectors.

an object is displaced to the point P'. The phase difference $\Delta\phi_i$ obtained using digital holographic interferometry is expressed as follows.

$$\Delta\phi_i = \boldsymbol{e}_i \cdot \boldsymbol{d} \tag{1}$$

The displacement vector and the sensitivity vector each have components in the x, y, and z directions. These values are expressed as follows:

$$\Delta\phi_i = \begin{pmatrix} e_{ix} & e_{iy} & e_{iz} \end{pmatrix} \begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} = e_{ix}d_x + e_{iy}d_y + e_{iz}d_z, \tag{2}$$

where $\boldsymbol{e}_i = (e_{ix}, e_{iy}, e_{iz})$ and $\boldsymbol{d} = (d_x, d_y, d_z)$.

When image sensors 1, 2, … N are located at independent positions, N sensitivity vectors are obtained. In this case, Eq. (2) can be rewritten as Eq. (3),

$$\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \vdots \\ \Delta\phi_N \end{pmatrix} = \boldsymbol{S}\begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} \tag{3}$$

where subscripts 1, 2, … N represent each imaging device. The matrix $\boldsymbol{S}$, called a sensitivity matrix, is defined as Eq. (4).

$$\boldsymbol{S} = \begin{pmatrix} e_{1x} & e_{1y} & e_{1z} \\ e_{2x} & e_{2y} & e_{2z} \\ \vdots & \vdots & \vdots \\ e_{Nx} & e_{Ny} & e_{Nz} \end{pmatrix} \tag{4}$$

Each element of this matrix is a constant number provided by the positional relationship between a light source and the corresponding imaging device. When the pseudo inverse matrix $\boldsymbol{S}^+$ of the sensitivity matrix $\boldsymbol{S}^+$ is defined in Eq. (5) and Eq. (3) can be rewritten as Eq. (6).

$$\boldsymbol{S}^+ = (\boldsymbol{S}^T\boldsymbol{S})^{-1}\boldsymbol{S}^T = \begin{pmatrix} f_{1x} & f_{2x} & \cdots & f_{3x} \\ f_{1y} & f_{2y} & \cdots & f_{3y} \\ f_{1z} & f_{2z} & \cdots & f_{3z} \end{pmatrix} \tag{5}$$

$$\begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} = \boldsymbol{S}^+\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \vdots \\ \Delta\phi_N \end{pmatrix} \tag{6}$$

This equation means that the displacement components d_x, d_y and d_z can be obtained from the phase differences $\Delta\phi_1$, $\Delta\phi_2$, … $\Delta\phi_N$ that are obtained by each image sensor. The displacement components d_x, d_y and d_z for the directions x, y and z, respectively, are expressed as follows:

$$d_x = \sum_{k=1}^{N} f_{kx}\Delta\phi_k,\ d_y = \sum_{k=1}^{N} f_{ky}\Delta\phi_k,\ d_z = \sum_{k=1}^{N} f_{kz}\Delta\phi_k \tag{7}$$

That is, the displacement distributions can be derived from the phase difference distributions obtained from the imaging sensors 1, 2, … N.

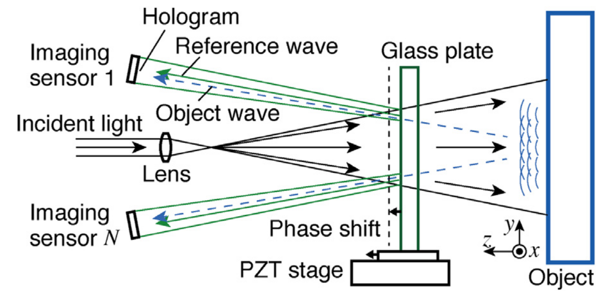

Fig. 2. Optical system for generating reference waves using a glass plate.

3. Generating reference waves using a glass plate

In conventional methods, each imaging sensor needs a reference wave divided by a half prism. It is a problem that N half prisms are necessary to produce reference waves into each imaging sensors in the case that N imaging sensors are used. The feasibility is however low.

Authors therefore proposed an optical system for generating reference waves using a glass plate as shown in Fig. 2. An incident light, a glass plate and an object are arranged in straight line. The normal directions of both the glass plate and the object are in accordance with the optical axis of the incident light. The glass plate is attached to a PZT stage to move to the normal direction. The back surface of the glass plate has an antireflection coating. N imaging sensors are located around the incident light, as shown in Fig. 2. The normal direction of each imaging sensor faces the center of the object.

A spherical incident wave is produced by a lens. A part of the incident wave is reflected onto the surface of the glass plate in the direction of the imaging sensors as reference waves. The transmitted incident wave illuminates the surface of the object. The scattered incident wave on the surface of the object reaches each imaging sensor by passing the glass plate as object waves. It is better that the surface of the glass plate has an antireflection coating to reduce the intensity of the reference wave. The reason is that the reference wave reflected on the glass surface without an antireflection coating is much higher than the object wave scattered from the object surface. A digital hologram generated from the reference wave and the object wave on each imaging sensor is recorded by each imaging sensor. Note that the pitch of interference fringe patterns depends on the wavelength and the difference of the incident angle on an imaging sensor between object wave and reference wave and note that the pitch of interference fringe patterns is enough larger than the pixel pitch of the imaging sensors to analyze the phase of the fringe pattern with phase-shifting method. Therefore, it is better to adjust the distance between the object and the glass plate to the distance between a center point of the incident spherical wave and the glass plate in order to obtain the larger pitch of interference fringe pattern on the imaging sensor. The phase of the reference wave can be shifted by moving the PZT stage on which the glass plate is located.

Using this optical setup, reference waves with shifting phases to each imaging sensor can be generated with a compact optical setup. A sensitivity vector for each imaging sensor is defined at the bisector of the angle between the optical axis of the incident light and the object wave to each imaging sensor. Therefore, N sensitivity vectors can be obtained using this optical setup.

4. Calibration method using a reference plate shifted with a 3-axes PZT stage

A calibration method for obtaining a sensitivity matrix using a reference plate is shown. Fig. 3 shows an optical system in the calibration process using a 3-axes PZT stage. A scattering flat plate is used as the reference plate. The reference plate is attached to the 3-axes PZT stage. The reference plate is located at the position of the object, as shown in