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Dynamic out-of-plane deformation measurement using virtual speckle patterns

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ABSTRACT

The novel measurement method based on the virtual speckle patterns has been reported. This method has the feature of analyzing the deformation map of an object in high resolution without any information except for speckle pattern images under a deformation process. In this paper, the method is applied to the measurement of dynamic events including a complex deformation distribution. The optical system of the method is improved in order to deal with the complex deformation distribution, which includes the increase and the decrease distributions. In experiments, the phenomenon of collision of the metal sphere on the thin polymer film is analyzed. The method can analyze the large deformation measurement of dynamic events, which cannot be measured by ordinary methods. It is confirmed that the measurement accuracy of this method even in measurements of dynamic events is high.

1. Introduction

The speckle interferometry is a useful deformation measurement method for measuring objects with diffusing surfaces in high resolution. Generally, speckle patterns before and after the deformation of measured objects are grabbed as the information concerning the deformation process. And, specklegrams are obtained by calculating the square of the difference between them. Then, fringe images concerning the deformation can be drawn as specklegrams. The quantity of a deformation can be extracted from the specklegrams by using fringe analysis methods [1–4]. Furthermore, electronic speckle pattern interferometry (ESPI) has been developed by introducing TV camera system to the speckle interferometry [5,6]. This method has been also improved to a high-resolution measurement method by introducing fringe scanning methods [7,8].

When fringe scanning methods are introduced to the speckle interferometry, temporal phase-shifting methods and the spatial phase-shifting methods are generally used [9]. In temporal phase-shifting methods, which control the phase of the reference beam, at least three sheets of fringe images are required for the fringe analysis [10–12]. So, some special optical systems, for example, multi-camera technologies [13–16], are used to carry out dynamic deformation and high-resolution measurements.

On the other hand, when spatial fringe analysis methods which employ the carrier fringe information are used, two sheets of speckle patterns before and after the deformation and another speckle pattern with a reference phase information are required to produce the carrier fringe image and the deformed carrier fringe image [17,18]. In these analysis methods, when the quantity of deformation of the measured object becomes large, the areas of speckles before and after the deformation come not to overlap spatially. Then, the speckles, which are related in each speckle pattern, cannot be spatially superimposed in the calculation process of the specklegram. As a result, fringe image cannot be also observed as a specklegram. Of course, the fringe analysis cannot be executed under this situation.

In order to avoid these situations, some fringe analysis methods, which can detect phase maps by using only one sheet of fringe image, have been reported [19–21]. Furthermore, the measurement including a large deformation of an object has been performed by using temporal speckle pattern interferometry (TSPI) [22,23]. In TSPI, the deformation process of the object is recorded sequentially as a series of speckle patterns by a high-speed camera. The deformation information is analyzed from these speckle patterns by Fourier transform. Though this measurement method can detect the large deformation of the object, the measuring accuracy of the method is not enough for nanometer-order measurement. Unless problems of the ambiguities in the results by Fourier transform at the start and the end points of the calculation can be solved, it would be difficult to improve directly the measurement accuracy of TSPI. There are usually ambiguities in calculation of Fourier transform, even if the

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optimum window function is used in the transformation. This problem cannot be avoided perfectly in the calculation of TSPI. Additionally, the CCD which has higher speed grabbing function also is required to use this method as higher-accuracy measurement method. Under these situations, the new method, that has higher resolution and more precise than TSPI has been developed [24] to solve the problems of TSPI.

In the new method, the information concerning the deformation process is successively recorded as a series of the speckle patterns during the deformation of an object. Then, the fringe analysis can be performed by using only the information in the deformation process. Virtual speckle patterns are used in this new method. However, there are also problems with the method: this method requires the condition of the monotone-increase (or -decrease) in phase distribution of the measured object. So there are difficult problems in practical use, when the measured object is deformed complexly.

In this paper, the dynamic measurement by a new method, which uses virtual speckle patterns, is reported. Then, the problem of the monotone-increase is also solved by improving the optical system.

From experimental results, it is confirmed that the new method can be employed in the large deformation measurement of dynamic events, which cannot be measured by ordinary methods. And, it is also confirmed that the measurement accuracy of this method is as high as that of the ordinary methods for deformations, that can be measured by ordinary methods.

2. Production of virtual speckle patterns [24]

In the optical system shown in Fig. 1, intensity of point P_0 would change when the object is deformed as shown by white arrows. In this case, intensity of point P_0 changes sinusoidally, in the same way as intensity of point P_1 in a speckle pattern shown in Fig. 2, when the object is deformed. The period of this sine curve is equivalent to a half of the wavelength of the laser.

The intensity distribution as shown in Fig. 2 at every pixel can be also recorded on each pixel of CCD during deformation process. When intensity distribution concerning the deformation process at every pixel is analyzed one dimensionally by Hilbert transform, the sine and the cosine components concerning the intensity distribution can be estimated. Then, the one-dimensional phase map at every pixel concerning the deformation can be detected by calculating the arctangent function of the ratio between the sine and the cosine components. These phase maps are data concerning time. Here, phase values are sampled synchronously from the phase maps of each pixel. Furthermore, when the sampled phase information at every pixel is arranged two dimensionally,

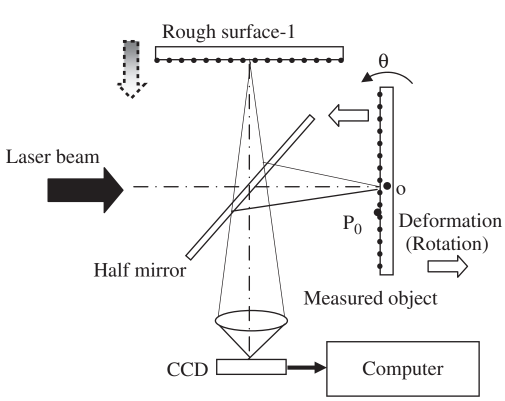

Fig. 1. Optical system.

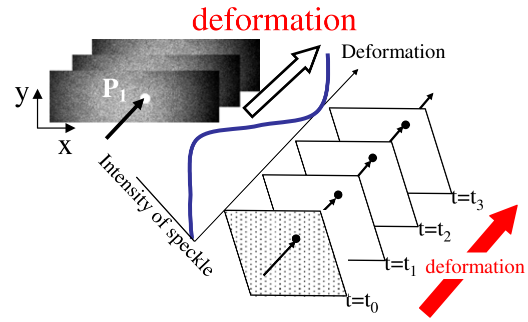

Fig. 2. Change of intensity of speckle in deformation process.

the two-dimensional phase map, $\varphi(x,y)$ concerning deformation process at arbitrary time can be estimated.

In much the same way as the estimation of two-dimension phase map, the amplitude of the intensity of each speckle, $B(x,y)$, at arbitrary time can be estimated by synthesizing the sine and the cosine components calculated by Hilbert transform. And, the bias component of each speckle, $A(x,y)$, at arbitrary time can be also estimated using the low-frequency component of the result of Fourier transform.

Under these calculations, intensity distribution ($I_s(x,y)$) at any point of the speckle pattern can be estimated in accordance with the intensity model of the speckle pattern shown in Eq. (1) by using phase distribution ($\varphi(x,y)$), amplitude distribution ($B(x,y)$), and bias distribution ($A(x,y)$):

$$I_s(x,y) = A(x,y) + B(x,y)\cos\{\varphi(x,y)\} \tag{1}$$

Furthermore, the speckle pattern which includes the spatial carrier information can be estimated by substituting the spatial phase information into Eq. (1). The intensity model of the speckle pattern including the spatial carrier information is given as

$$I_{sc}(x,y) = A(x,y) + B(x,y)\cos\{\varphi(x,y) + \omega_c x\} \tag{2}$$

where ω_c is a spatial carrier frequency. Recently, out-of-plane and in-plane deformation static measurements have been performed by using amethod which employs virtual speckle patterns. However, it was confirmed that there were problems concerning monotone-increase phase distribution in these analyses. This problem can be observed in Fig. 1. For example, the direction of the deformation of measured object is different between the upper side and the lower side of the center (o) of the rotation as shown in Fig. 1. As shown, white arrows, the phase of the fringes in the area under the center would increase with deformation. And, the phase of the fringes in the upper side of the center would decrease. So, when intensity distributions are given from deformation process as shown in Fig. 1, the same sinusoidal curves shown in Fig. 2 are detected in both areas of the upper and the lower sides of the center. That is, phase distribution, which has increase and decrease, cannot be analyzed by this method. However, such a problem concerning the direction of the deformation can be readily solved by moving the rough surface-1 which is a reference of the optical system shown in Fig. 1.

Now, another new optical system is proposed (as shown in Fig. 3) to measure the phase map which has in it increases as well as decreases. Then, the rough surface (reference surface) in the optical system is moved by PZT actuator. By using the new optical system, the complex deformation of the measured object can be analyzed by using only the information of deformation process.