Design of Phase-shifting ESPI System for 3D Deformation Measurement

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Abstract. It designs the phase-shifting ESPI (electronic speckle pattern interferometry) systems for 3D deformation measurement. The first design applies common optics, single laser source and two PZTs to introduce five testing beams, in which two beams are phase-shifted. By this system, in-plane and out-plane deformation can be tested by switching the projecting beams and 3D deformation of the object can be calculated. The testing is closely dynamic. The second design applies a one to five beam-splitting fiber to simply and compact the system. In this system, the laser beam is divided into five sub-beams as the testing rays. On the heads of two sub-fibers, PZTs are attached to introduce phase-shifting. By analysis, the system error by this phase-shifting mode can be omitted. In this system, the in-plane and out-plane deformation are tested by the same switching mode as the first design, which means that the dynamic characteristic is determined by the switching speed. It describes the two designs and analyzes briefly.

1. Introduction
The testing of deformation, strain, stress and other status messages are demanded widely in industry and research. Electronic speckle pattern interferometry (ESPI) and digital correlation technique of images are two of important ways to realize dynamic and non-contact testing [1-5]. Take Dantec Ettemeyer GmbH cop. as the representatives, it has produces a few kinds of measurement instruments [6]. The aim of this paper is to design ESPI system for 3D deformation measurement with the following demands: (1) realizing the measurement of spatial deformation; (2) good dynamic characteristic; (3) getting quantitative deformation; (4) system is compact with less optics; (5) with a single laser source. According to these demands, it designs two ESPI systems which combine phase-shifting technique. One applies common optics and other uses fiber. The paper describes the systems and analyzes briefly.

2. ESPI system on common optics for 3D deformation measurement

2.1. Design of the ESPI system on common optics for 3D deformation measurement
The sketch map of the design is shown in figure 1. The system uses laser 1 as the light source which projects laser into beam-splitter 2. The transmission beam is projected into beam-splitter 5 after passing by shutter 3 and divided into transmission beam and reflected beam. Between them, the reflected beam becomes light A after reflected by the reflector 7 and the transmission beam becomes...
light B after passing the reflector 6 and 8. Light A and B shine the tested surface after the same beam expander 12 to form the testing system of in-plane deformation along the vertical direction. A PZT is attached on reflector 6 to introduce phase-shifting for light B. The reflector 8 can rotate in order to import light B’ with phase-shifting. Just light A and B’ form the testing system of out-plane deformation. The beam reflected by beam-splitter 2 is transported into beam-splitter 10 passing shutter 4 and divided into transmission and reflected beams. The transmission beam becomes light C after reflected by reflector 11. The reflected light of beam-splitter 10 becomes light D after passing reflector 14. A PZT is attached on the reflector 14 to introduce phase-shifting for light D. Then the light C and D shine the tested surface and form the testing system of in-plane deformation along the horizontal direction.

In the design system, “4+1” algorithm [7] is applied to realize the quantitative testing, in which the system captures four phase-shifting images before deformation and one image after deformation. And the measurement of out-plane and in-plane deformation are switched by shutters. So the dynamic characteristic of the system is determined by the switching speed. By this system, it can realize 2D or 3D deformation measurement.

\[
\sin \theta \frac{4\pi}{\lambda} u \sin \theta
\]

In which, \(\theta\) is the angle between the light and the normal direction of the tested surface, and \(u\) is the deformation along horizontal direction.

**Figure 1.** Sketch map of 3D ESPI system for deformation measurement.

2.2. Calculation of 3D deformation

2.2.1. In-plane deformation. In the horizontal direction (in plane XOZ), light C and D shine the object symmetrically. There is the following relationship:

\[
\Delta \varphi_1 = \frac{4\pi}{\lambda} u \sin \theta
\]
In the vertical direction (in plane YOZ), light A and B shine the tested surface symmetrically. There is the following relationship:

\[
\Delta \phi_2 = \frac{4\pi}{\lambda} v \sin \alpha
\]  

(2)

In which, \(\alpha\) is the angle between the light and the normal direction of the tested surface, and \(v\) is the deformation along vertical direction.

2.2.2. Out-plane deformation. Rotating reflector to shine light to reflector 9 and then to the tested surface. Light A and B’ form the testing beams for out-plane deformation measurement. There is the following relationship:

\[
\Delta \phi_3 = \frac{2\pi}{\lambda} [w(1 + \cos \alpha) + v \sin \alpha]
\]  

(3)

In which, \(\alpha\) is the angle between the light and the normal direction of the tested surface and \(w\) is the deformation along the out-plane direction.

2.2.3. Calculating the 3D deformation. By equation (1) to (3), there is:

\[
\begin{bmatrix}
\Delta \phi_1 \\
\Delta \phi_2 \\
\Delta \phi_3
\end{bmatrix} =
\begin{bmatrix}
\frac{4\pi}{\lambda} \sin \theta \\
\frac{4\pi}{\lambda} \sin \alpha \\
\frac{2\pi}{\lambda} \sin \alpha \quad \frac{2\pi}{\lambda} (1 + \sin \alpha)
\end{bmatrix}
\begin{bmatrix}
u \\
v \\
w
\end{bmatrix}
\]

(4)

So by equation (4), the deformation along three vertical directions can be calculated.

3. ESPI system on fiber for 3D deformation measurement

3.1. Design of the ESPI system on fiber for 3D deformation measurement

Fiber has flexibility in optical system, proper application can reduce the number the optics and make system compact. The paper introduces a one to five fiber to the ESPI system, shown in Figure 2. The system applies this fiber to obtain five sub-beams as the testing beams.

Shown in Figure 2, laser 1 is the light source. The laser is coupled into the fiber 4 by microscope 2 and precision adjustor 3. In fiber 4, the light is divided into five sub-beams for sub-fiber 11, 12, 13, 14 and 15. The sub-fiber 11 shine light to splitter 7 after passing through shutter 9 and expander and collimator 10; Sub-fiber 12 and 14 are put in the horizontal plane and shine the object 22 symmetrically vertical to the normal of the object surface. PZT 17 is attached on the out-put head of sub-fiber 14 to introduce phase-shifting. Thus they form the testing system of in-plane deformation along horizontal direction; Sub-fiber 13 and 15 are set in the vertical plane and shine the object 22 symmetrically vertical to the normal of the object surface. PZT 16 is attached on the out-put head of sub-fiber 15. Thus they form the testing system of in-plane deformation along vertical direction.

At the out-put head of sub-fiber 12, 13, 14, 15, shutter 18, 19, 20, 21 are put to control the order of deformation testing. When testing the in-plane deformation along the vertical direction, shutter 18 and 21 are open to pass the light and shutter 9, 19 and 20 are closed; When testing the in-plane deformation along the horizontal direction, shutter 19 and 20 will be open and shutter 9, 18 and 21 will be closed. When testing the out-plane deformation, shutter 9 and 19 will be open and other shutters have to be closed. By the same CCD, the deformation fringe patterns are captured in certain order.

In the design shown in Figure 2, adjacent to the out-put head of sub-fibers, proper expanding lens can be set to enlarge the diameter of the projecting beams. But the phase-shifting error must be considered.
In this design, for applying a fiber, the system is compact and the number of the optics is reduced compared with the system with common optics. The system also easily gets a small size.

![Diagram of ESPI system by fiber](image)

1. Laser  2. microscope  3. precision adjuster of fiber  4. one to five fiber  5. computer  6. CCD  7. beam-splitter  8. imaging lens  9, 18, 19, 20, 21. shutter  10. beam expander and collimator  12, 13, 14, 15. sub-fiber  16, 17. PZT  22. tested object

**Figure 2.** Sketch map of the ESPI system by fiber.

3.2. Analysis of phase-shifting error

In the designed ESPI system, the central sectors ensuring the measurement function include: the adjusting of the directions and positions of the sub-beams; the interference between the sub-beams and the phase-shifting mode. The first two questions are ensured by the mechanical parts and the purchased fiber. Now it will analyze whether the phase-shifting mode applied in the designed system is proper.

The transmission distance of light in fiber is changeless. When the sub-fiber is moved by PZT, the optical distance to the object surface changes. To simplify the analysis, it is supposed that the light shines the object near the optical axis, as shown in figure 3. It will check the additional phase-step windage between the edge point \( d_1 \) and the middle point O.

![Diagram of phase-step error](image)

**Figure 3.** Analysis of the phase-step error.

Sub-fiber is moved from position A to position B. The changing of optical length is \( L \) for the middle point O. For the edge point \( d_1 \), the changing is \( L / \cos(\theta / 2) \). So the phase-step error of the edge point relative to the central point is

\[
\Delta \varphi_{\text{error}} = \frac{1 - \cos(\theta / 2)}{\cos(\theta / 2)} \frac{2\pi}{\lambda} L
\]
And the position changing of the edge point is \( d_{e1} = L \cdot \tan(\theta/2) \). Supposing the splaying angle of the fiber is 20 degree, the scale of the tested surface is less than 100*100mm, the pixel number of CCD is 768*576 pixels and the wavelength of the laser source is 0.6328\(\mu\)m. The analysis result is shown in table 1.

| \( \theta \) | Phase-steps at middle point | Phase-step error at the edge points | Position windage at the edge points (\(\mu\)m) |
|---------------|-----------------------------|-----------------------------------|----------------------------------|
| \( \pi/2 \)   | 0.0077\(\pi\)               | 0.0279                            |
| \( \pi \)     | 0.0154\(\pi\)               | 0.0558                            |
| 20°           | 0.0231\(\pi\)               | 0.0837                            |
| 2\(\pi\)      | 0.0309\(\pi\)               | 0.1116                            |

From the table 1, it can be seen that the phase-step error and position windage by the phase-shifting mode applied in the designed system can be omitted.

4. Conclusion
The paper designs two kinds of phase-shifting ESPI system for 3D deformation measurement. The first design applies common optics, so it is easy to set up. But it needs many elements and has a high demand for the adjustment. The second design introduces fiber to simply the structure and makes the system compact and smaller. One demand is that the beams from five sub-fibers must hold certain interference between each other. The error caused by the phase-shifting mode applied in the designed system should also be paid attention to, especially when the beam spraying angle of the sub-fiber is big. If the error can’t be accepted by the measurement precision, other phase-shifting modes must be considered. The two designs complete the in-plane and out-plane deformation measurement by switching the projecting lights, so the dynamic characteristic of the two designs are all determined by the shuttering speed. In algorithm, they apply phase-shifting algorithm to get the quantitative results. By now it has reached our initial target described in the introduction. Of course, in actual application of the two designs, some detail sectors must be done and analyzed.

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