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Calibration of the DOE lens array based Multipoint Diffraction Strain Sensor

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ABSTRACT

Multipoint Diffraction Strain Sensor (MDSS) is a non-contact whole field strain sensing system. DOE-based lens arrays are designed and used to replace the typical micro-lens array in our MDSS system. These DOE patterns are displayed on the liquid crystal spatial light modulator. So with different focal length, tunable strain sensitivity is achieved. Calibrations are performed to test the measurement accuracy and precision of the system.

Keywords: DOE lens array, LC-SLM, Diffraction Strain Sensor, tunable strain sensitivity

1. INTRODUCTION

Multipoint Diffraction Strain Sensor (MDSS) is a non-contact whole field strain sensing system[1-4]. It is composed of a typical moiré interferometer with a micro lens array for wavefront sensing as the Shack-Hartmann Sensor. Both of the high sensitivity as an interferometer and the high speed of post-processing are achieved, since the cumbersome fringe analysis is avoided. And the strain is directly calculated by differencing the centroid results from the focal spot images sampled by the micro lens array before and after deformation.

One key component in this system is the micro lens array. The parameters of the lens array determine the system sensitivity and the quality of the focused spots, thus the centroid results and the measurement precision. In MDSS system, the DOE-based micro lens arrays displayed on the LC-SLM are designed to replace the traditional physical lens array[2, 5]. The most advantage of these DOE-based lenses on the SLM is that their parameters, such as focal length, lens diameter and lenslet interval, are tunable directly by software. Besides, the procedure for fabrication and installation of the physical lenses are avoided.

In this paper, firstly the design of DOE micro lens array is briefly introduced. Then the calibration is performed with different DOE lens arrays. The calibration results of system accuracy and precision are shown.

2. SYSTEM SETUP AND PRINCIPLE

Multipoint Diffraction Strain Sensor (MDSS) is composed of a moiré interferometer, a liquid crystal spatial light modulator (LC-SLM) and a digital camera. DOE patterns are designed beforehand and displayed on SLM, controllable by software so it is convenient to adjust the measure range and strain sensitivity.

As shown in Fig.1, two monochromatic and collimated laser beams illuminate an optical grating attached on specimen. In our experiment, a 1200 lines/mm cross grating is used. The first order diffracted beams are normal to the grating surface and collected by a micro-lens array displaying on the SLM screen. The spot images before and after specimen deformation are captured. Centroids of the spots are calculated using a MATLAB[®] program and strain which is proportional to spots shifting is then acquired.

Figure 1 Schematic of MDSS based on a moiré interferometer with a LC-SLM

The relation of spots shifting and normal strain is given below:

$$\varepsilon_x = \frac{du}{dx} = \frac{\Delta x_2 - \Delta x_1}{2f \sin \alpha} \quad (1)$$

$$\varepsilon_y = \frac{dv}{dy} = \frac{\Delta y_2 - \Delta y_1}{2f \sin \alpha} \quad (2)$$

$\varepsilon_x, \varepsilon_y$ are strain along x-direction and y-direction respectively. Δx is spot shift in x direction under U-field illumination and Δy is spot shift in y direction under V-field illumination. f is focal length of lens array, α is illuminating angle of laser beam.

Under U-field illumination, the rotation angle (part of shear strain) is given by:

$$\Delta \phi = \frac{du}{dy} = \frac{\Delta y_2 - \Delta y_1}{2f \sin \alpha} \quad (3)$$

Similarly under V-field illumination, the rotation angle (part of shear strain) is given by:

$$\Delta \phi = \frac{dv}{dx} = \frac{\Delta x_2 - \Delta x_1}{2f \sin \alpha} \quad (4)$$

From above equations, it is seen that the strain sensitivity is inversely proportional to the focal length of lens array. Thus theoretically the sensitivity of the system is tunable by alternating the focal length, which is easily done by alternating DOE patterns displayed on SLM by software. Notice that although the RHS of equation (1)(4) and (2)(3)

seems identical, however they are measured under different illumination conditions (U-field and V field).

3. DOE MICRO-LENS DESIGN

The SLM used in the experiment is LC2002C, manufactured by HOLOEYE. It is a liquid crystal micro display in transmission mode with a resolution of 800 x 600 in pixels. And the pixel size is 32 μm . It is operated as a complex Amplitude and Phase Modulation. These parameters such as resolution and pixel size are considered in the lens design.

Since the SLM screen is composed by discrete pixels, phase quantification process is employed for each pixel. The lens arrays are designed according to the phase function of a single lens in Cartesian coordinates:

$$\phi(i, j) = k \frac{(i^2 + j^2)d^2}{2f} \quad (5)$$

where i and j are the column and row index of each pixel in the SLM. d is the pixel size of the SLM. f is the focal length of the lens. k is the wave vector which is determined by:

$$k = \frac{2\pi}{\lambda} \quad (6)$$

Finally a modulus operation is applied on the phase values. Then the remainder is scale from 0 to 255 and rounded into integers. The gray value is:

$$I(i, j) = \text{mod}[\phi(i, j), 2\pi] * \frac{255}{2\pi} \quad (7)$$

This gray value of a designed lens can be saved into an 8-bit image file.

Single lenses with 3 different focal lengths (80mm, 120mm and 160mm) are generated with a diameter of 50 pixels. Then the single lenses are replicated to compose a 16x12 lens array as shown in Fig 2. They are used in the calibration measurements. Generally this kind of periodic design will introduce higher order diffraction spots. However they can be eliminated by proper design[6, 7] or moved out as noise during centroid procedure[8].

Fig. 2. Lens arrays with different focal length: (a)f=80mm;(b)f=120mm;(c)f=160mm

4. CENTROID DETECTION AND CALIBRATION PROCEDURE

Centroid detection is a crucial part in the strain measurement. In our experiments, a centroid algorithm based on adaptive thresholding and windowing method[8] is used. As shown in Fig 3(b), Windowing is useful to eliminate higher order diffraction spots. Adaptive thresholding is necessary when the intensity of spots fluctuates and it is also capable of suppress influence caused by noises. And for spot image in ideal condition as shown in Fig. 3(a), above mentioned methods do not increase much processing overhead cost.

Fig. 3 Centroid results. (a)ideal spot image; (b)spot image with higher order and noise

Whole field (multi-point) measurement capability is one of the advantages of MDSS, this feature can also be used for calibration purpose. Two strategies are used for calibration: for accuracy estimation, a rotation stage is used. A series of sequential rotations is applied on the rotation stage and measured. For each specific rotation applied, the measurement results are rotations from multi-points in distributed subareas. The average of the rotation values is compared the reading on the rotation stage to verify the system accuracy. And the stand deviation of the multi-point results is used as an indicator of the precision.

The precision of the whole system is evaluated by its repeatability. The three different lens arrays as shown in Fig. 2 are used in calibration under different camera exposure time. During the test, the specimen and the whole system are maintained stably and spot images are captured sequentially. In each test, k=100 consecutive images are taken randomly during the test procedure. And due to the limited CMOS size, there are N=72 focal points are captured in each image. The two different exposure times are used to simulate different ambient light tolerance. The centroid results are analyzed statistically with Eq. (8). The standard deviation of the measurement results is used to evaluate the system precision.

$$\nu^2 = \frac{1}{N} \sum_{n=1}^N \left(\frac{1}{K} \sum_{k=1}^K \left(x_k - \bar{x} \right)^2 + \left(y_k - \bar{y} \right)^2 \right) \quad (8)$$

5. RESULTS AND DISCUSSION

To verify the accuracy, the sample is fixed on the rotation stage and rotated by 7.2, 12, 16.8 and 21.6 arc minutes respectively. The lens array with 120mm focal length is used for measurement. The measured rotations are 7.02, 12.14, 17.32 and 21.86 arc minutes with standard deviation of 0.09, 0.08, 0.09 and 0.09 arc minutes respectively. Considering the minimum scale of the rotation stage is 2.4 arc minutes, the measurement results are in good agreement with the rotation applied. The system accuracy and precision are relatively high (less than 4% error).

Figure 4 Plot of rotations by measurement vs. rotations applied. The error bar is calculated by the standard deviation of measured strain values and blue line is a 45° straight line for reference

According to Eq. (1)-(4), there is a linear relation between rotation (part of shear strain) and the uniform normal strain. The factor is $\Delta\phi / \varepsilon = 180 \times 60 / (\pi 10^6) = 0.0034 \text{ arc min} / \mu\epsilon$. Take the maximum standard deviation 0.1 arc minutes for instance, the equivalent standard deviation for strain measurement is $30 \mu\epsilon$. It is used to indicate the precision of the system (thus the strain sensitivity).

Above accuracy calibration is also relied on the rotation stage (which can only provide accuracy around the same level). So some external errors are introduced. However, the precision calibration procedure is free from external devices and the measurement results faithfully indicate the whole system performance.

As shown in Tab. 1, for 3 different focal lengths and 2 exposure time settings, the standard deviations are all less than 0.1 pixels. It can be generally concluded that the system precision is sub one-tenth pixel in the common experimental conditions. Substitute this conclusion to Eq.(1) or (2) with the camera pixel size ($12 \mu\text{m}$), the strain sensitivity can be calculated. And the results indicate the strain sensitivity can be improved with longer focal lengths and/or smaller camera pixel size.

Table 1. Standard deviation of centroid in different experimental conditions

Focal length (mm)	Exposure time (ms)	Standard deviation (pixel)	Sensitivity (micro strain)
80	20	0.0837	44.0
80	40	0.0727	38.2
120	20	0.0806	28.3
120	40	0.0862	30.2
160	20	0.0546	14.4
160	40	0.0646	17.0

6. CONCLUSION

Through the calibration, the accuracy of the MDSS system is verified with a rotation stage. The precision is $30\mu\epsilon / 0.1\text{arc minutes}$ with DOE lens array of 120mm focal length. In common measurement condition, the precision of the system reaches sub-one-tenth pixel. And the strain sensitivity is improved by using longer focal length lens arrays.

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