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Experimental Stress Analysis

Optical Sensor for Measurement of an Object In-plane Translation and Rotation by Speckle Correlation Method

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Abstract: The paper presents design and experimental verification of an optical sensor for non-contact detection and quantitative evaluations of both in-plane translation and rotation of object's surface by speckle correlation method. This sensor enables to detect both of the small deformation tensor components without change in geometrical parameters of the set-up and hence its conversion.

Keywords: Speckle, Speckle correlation, In-plane, Object translation, Object rotation

1. Introduction

Research in measurement of components of small deformation tensor by speckle correlation method has produced single-purpose optical sensors so far [1—5]. Measurement of different components requires change in geometrical parameters of a sensor and its complicated conversion. This paper presents design of an optical sensor enabling to detect in-plane translation and rotation of object's surface without its any conversion. Firstly, analysis of its measurement range and sensitivity is done. Then the sensor is verified experimentally.

2. Theoretical background

The sensor uses speckle [6, 7] the optical effect that is a result of interaction of coherent light and a rough object's surface. Let us suppose that the object's surface at a point P reflects incident coherent light emitted by a source point S (Fig. 1) at a distance of L_S from the object's surface forming an angle $\theta_S = 0°$ with the z-axis. Reflected light forms interference speckle field observed by a pair of cameras C_1 and C_2 included in two sub-sensors, one for detection of in-plane translation and the other for rotation of object's surface. Distances L_{OR} and L_{OT} between the cameras

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and the point P on the object's surface and observation angles θ_{OR} and θ_{OT} of the sub-sensors influence detection properties of each sub-sensor [4, 5]. Each camera detects corresponding speckle field displacements A_{XR} and A_{XT} in the X-axis direction through correlation of recorded intensity structures.

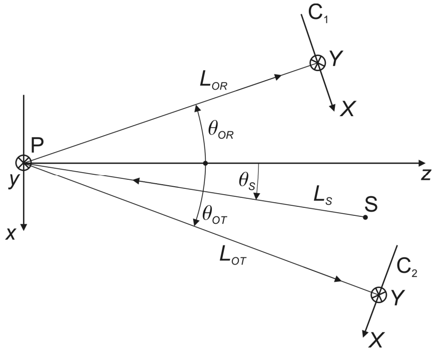

Fig. 1. Geometrical arrangement of the sensor for measurement of in-plane translation and rotation of object's surface.

In-plane rotation ω_y of object's surface (a component of small deformation tensor representing object rotation about y-axis) is then evaluated according to [5] as

$$\omega_y = \frac{A_{XR}}{L_{OR}\left(\dfrac{1}{\cos(\theta_{OR})}+1\right)}. \quad (1)$$

Supposing that the object's surface translates in x-axis direction only, in-plane translation a_x of object's surface (a component of small deformation tensor) can be calculated according to [4] as

$$a_x = \frac{A_{XT}}{\dfrac{L_{OT}}{L_S\cos(\theta_{OT})}+\cos(\theta_{OT})}. \quad (2)$$

3. Analysis of theoretical sensitivity and range of measurement by the sensor

Now, let us shortly consider sensitivity and range of measurement of in-plane rotation ω_y and translation a_x components by means of the sensor in Fig. 1. The measurement sensitivity and range depend crucially on the geometrical configuration of the sensor (on the geometrical parameters L_{OR} or L_{OT}, L_S, θ_{OR} or θ_{OT}, θ_S) and resolution power of used detector (the pixel size).

A numerical analysis for the following values and ranges of the geometrical parameters $L_S = 0.1$ m, $L_{OR} \equiv L_{OT} \in (0.1, 0.6)$ m, $\theta_{OR} \equiv \theta_{OT} \in (10, 40)°$ and for a possible range of the detected speckle field displacements A_{XR} and $A_{XT} \in (1, 100)$ pixels is performed. The pixel size is supposed to be 7.5 x 7.5 μm^2.

Using Eq. (1) theoretical range of measurement of rotation component ω_y is 0.01′ - 12.7′. Similarly by the use of Eq. (2) theoretical range of translation component a_x is 0.6 μm - 375 μm. The theoretical analysis also shows that for practical measurements of object's surface rotations within the limits from unites to tens of minutes and object's surface translations within the limits from tens to hundreds of micrometers uncertainty of measurements are less than 5%. These findings follow from the theory of uncertainties and errors [8].

Let show the theoretical measurement sensitivity of in-plane object's surface rotations (Fig. 2) and in-plane object's surface translations (Fig. 3) for the above mentioned values and ranges of the geometrical parameters. These theoretical sensitivities are evaluated for speckle field displacements A_{XR} = 100 pixels (in case of in-plane rotation) and A_{XT} = 10 pixels (in case of in-plane translation). It is evident that the measurement sensitivity increases with increasing distance between the camera and object's surface.

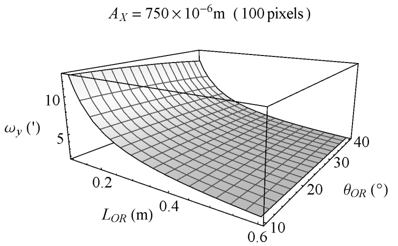

Fig. 2. Theoretical measurement sensitivity of in-plane object's surface rotation ω_y for the arrangement in Fig. 1.

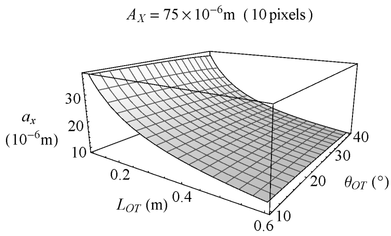

Fig. 3. Theoretical measurement sensitivity of in-plane object's surface translation a_x for the arrangement in Fig. 1.

4. Experimental verification of the sensor

Designed optical sensor uses a He-Ne laser as a source of coherent light. Its beam is directed upright to the object under investigation. A lens inserted between the laser and the object's surface focuses the beam into a point approximately that represents a source point at the distance L_S. The object is represented by an aluminium cuboid and placed on a special apparatus (Fig. 4), which consist of a linear stage mounted to a rotary stage. A CMOS detector with a row of 1244 pixels (pixel size 7.5 x 7.5 μm^2) captures the arising speckle field. Obtained data is then transferred to a PC and processed consecutively.

The measurement process itself proceeded as to in the following steps. The electronic linear stage with the object is translated 10 times in the *x*-axis direction by a constant distance with an accuracy of 0.1 μm. The arising speckle field is captured by the CMOS detector before and after each translation. Recorded frames are numerically processed in the PC for determining a position of the maximum of the normalized cross-correlation function of each two consecutive frames [4].

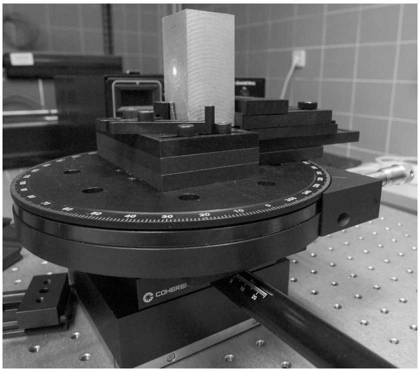

Fig. 4. A detailed view of an object under investigation placed on a special apparatus, which consist of translation and rotation stages.

The measurement process for rotation measurement is analogues. However rotation stage is not electronic but mechanic with a reading accuracy of 0.5′ and sensitivity 0.1′.

Measurements of rotation (from 0.5′ to 7.5′) and translation (from 10μm to 150μm) range are done. The rest parameters of the sensor are as follows: $L_{OR} \equiv L_{OT} = 500$ mm, $L_S = 100$ mm, $\theta_{OR} \equiv \theta_{OT} = 22.5^{\circ}$, $\theta_S = 0°$. Let us present some achieved results in tables Table 1 – Table 3.

Table 1. Measurement of in-plane rotation ω_y of object's surface rotated by 1′

n	A_{XR} [pixel]	$r_{1,2}$ [%]	ω_y [′]
1	-37	98.1	0.92
2	-42	98.1	1.04
3	-38	95.9	0,94
4	-38	97.5	0.94
5	-38	98.9	0.94
6	-40	98.9	0.99
7	-37	98.7	0.92
8	-37	99.0	0.92
9	-39	98.7	0.97
10	-39	98.5	0.97

Achieved result of measurement: $\omega_y = (0.95 \pm 0.01)\,'$

Table 1 presents values of in-plane rotation of object's surface rotated by 1′ in each step n of object rotation. Results of measurement of in-plane translation of object's surface translated by 10 μm in each step n of object translation are shown in Table 2. The measurements are repeated 10 times. Quantities A_{XR} and A_{XT} represent the speckle field displacements in pixels determined from the position of the maximum of the cross-correlation function. Correlation degree $r_{1,2}$ denotes maximal similarity measure, in percents, of two frames captured before and after the object rotation or translation. The detected rotation ω_y represents the rotation in angle minutes evaluated according to Eq. (1). and detected translation a_x represents the translation in μm evaluated according to Eq. (2). There are noted evaluated average mean values and its standard deviations below each table.

Table 2. Measurement of in-plane translation a_x of object's surface translated by 10 μm

n	A_{XT} [px]	$r_{1,2}$ [%]	a_x [μm]
1	-8	98.2	9.47
2	-9	98.4	10.65
3	-8	98.8	9.47
4	-8	98.7	9.47
5	-9	98.5	10.65
6	-9	98.6	10.65
7	-9	98.6	10.65
8	-9	98.4	10.65
9	-9	98.1	10.65
10	-8	97.8	9.47

Achieved result of measurement: $a_x = (10.2 \pm 0.2)$ μm

Table 3 summarizes achieved results of measurement for both rotation and translation of object's surface under investigation. The first and fourth columns of the table contain values of the measured rotation angles ω_y and translations a_x. Further means (the second and fifth columns of the table) represent the average values evaluated from repeated measurements of object's surface rotations and object's surface translations by the sensor. Finally the standard deviations (the third and sixth columns of the table) give information about variance between values of the repeated measurements.

Table 3. Results of the measurement of in-plane translation and rotation of object's surface under investigation by means of designed sensor

In-plane rotation			In-plane translation		
ω_y [′]	Mean [′]	Standard deviation [′]	a_x [μm]	Mean [μm]	Standard deviation [μm]
0.5	0.50	0.03	10	10.2	0.6
2.5	2.49	0.07	80	82.2	0.6
7.5	7.35	0.06	150	153.2	1.1

5. Conclusions

A sensor for detection of in-plane object's surface rotation and translation is presented. The sensor enables to detect both of the small deformation tensor components without change in geometrical parameters of the set-up. The sensor consists of two sub-sensors, each one for detection of the corresponding small deformation tensor component. Hence the designed sensor detects the components at the same time. Since the geometrical parameters of both sub-sensors are identical there is a possibility to use only one sub-sensor for detection either rotation or translation component.

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