Compensation for rigid body displacements in study of local deformations using electronic speckle pattern interferometry

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Abstract. The paper addresses techniques of optical compensation for rigid body displacements of objects undergoing deformation in measurement of in-plane displacements using electronic digital speckle pattern interferometry. Results of demonstration tests are presented. The proposed approaches may be useful, in particular, in study of mechanical properties of materials involving samples with stress concentrators.

Electronic speckle pattern interferometry (ESPI) is used to measure individual components of displacement vectors on surface of solids [1, 2]. The technique is based on recording of images of objects undergoing deformation with laser illumination. Images of objects with rough surface are formed by multiple chaotic speckles. Let two images of an object in different deformation states be recorded using a digit video camera and one picture area be subtracted from the other (e.g. using a proper Photoshop option). As a result, we have a ‘difference’ image of the object covered with a set of fringes. The emergence of these fringes may be explained as follows. Displacement of solids is accompanied by periodical changes in speckle intensity that causes their chaotic scintillation when the object shifts. This is due to changes in optical difference in motion of rays R illuminating individual points on the object. However speckle intensity distribution on a current picture area will be fully reconstructed in sites where the change in the motion difference is equal to the whole number of laser wave lengths \( \lambda \), i.e. \( R = \lambda N \), where \( N = 0, \pm 1, \pm 2 \). Such sites formed by correlated random speckle patterns will have zero intensity after subtraction of two picture areas recorded. Each of these sites looks like an individual dark fringe. Displacement value in a point of the object on such a fringe may be calculated by its interference order \( N \). Direction of the displacement depends on optical arrangement of the measurement set.

Let the object be illuminated with two symmetrical laser beams simultaneously, as shown in figure 1. (The conventional arrangement type has no glass plate in front of the camera lens. The purpose of the glass plate will be described further). In this case visualized fringe patterns will carry information about in-plane displacements \( U(x, y) \) along the X axis only. Interpretation of such patterns (interferograms) is done by formula

\[
U(x, y) = \frac{N(x,y) \lambda}{2 \sin(\alpha)}
\]

where \( \alpha \) is the angle of incidence of illuminating beams.
This fringe formation principle implies that individual similar speckles have the same (or next to the same) position in two images recorded. (The term ‘similar’ means here that these speckles are generated by the same microscopic site on the object surface). However displacement of the object under deformation is accompanied by displacement of the speckle pattern on its image in proportion to the scale factor. Therefore, in conventional speckle-pattern interferometry the upper range of displacement measurement is limited by speckle average size. The less the overlap area after superposition of pictures, the lower the fringe contrast in the difference image. If local displacement is greater than the speckle size, no fringes are formed.

Figure 1. Interferometer optical set-up to measure in-plane displacements of object undergoing deformation

This effect significantly reduces ESPI capacity. In particular, it makes difficult study of deformation state of an object against the background of its displacements as a rigid whole. Such situation is observed, for instance, in tensile testing of samples with stress concentrators (figure 2a). A zone around the concentrator is here of special interest. However, loading of the sample in a test machine causes displacement of this zone due to deformation of a part of the sample beginning from the site of its fixation in a stationary gripper. The axial displacement picture will have satisfactory contrast under low load (figure 2b). However the fringe contrast decreases gradually till complete disappearance of the fringes as the load increases (figure 2c). Note that residual displacements after elastic-plastic deformation and sample unloading concentrate mainly in the concentrator area which results in a rather high fringe contrast on the corresponding interferograms. See, for example, residual displacement fields at the start of plastic deformation in figure 2d. The interferogram in figure 2e was obtained after emerging of cracks during sample cyclic loading.

A special experiment was developed to demonstrate this phenomenon in a greater detail. A plate making a small rotation $\Omega$ around normal $Z$ in its plane (XY) was taken as the experimental object, figure 3a. The rotation center was within the observation area. It is easy to show that expected fields of in-plane components of displacements $U$ and $V$ are described by linear relationships, i.e.

$$U = \Omega y, \quad V = -\Omega x$$  \hspace{1cm} (2)

Figures 3b-e show typical interferograms of such displacement fields. They are obtained using two identical optical set-ups situated at a 90° with respect to each other around the axis $Z$. As seen,
The equidistance fringe spacing is decreasing as Ω increases, which is in accordance with formulas (1) and (2). The observed pictures are of a good quality at the entire operation surface at small rotation angles (figures 3b, c), but the contrast at the periphery is decreasing significantly to eventual complete fringe disappearance with increase in Ω. This is due to rise in magnitude of the plate point displacement as the distance from the rotation center becomes longer (figures 3d, e). Note, that the conventional border of the area with satisfactory fringe contrast is described here by a circumference as a line of equal values of displacement vector modulus. Therefore, it is this very characteristic that influences the loss in fringe contrast rather than values of individual components U or V.

The rigid body displacements may be compensated for using special computer software through reciprocal shifting of two digitized picture areas before subtraction. (Directions of illumination of all points of the object should remain unchanged when the object is moved. Light beams with a plane wave front are used for this purpose, as demonstrated in figure 1). However, this approach limits the picture area shifts to discrete steps of no less than one pixel, which hampers achieving maximal possible fringe contrast in interferograms. Relationship between the value of the compensated displacement and the pixel physical size is a determinant factor here, the desired value being a whole number. There is a simple technical expedient to avoid the above mentioned limitation. Interferometer conventional optical set-up includes an additional optical element as a plane-parallel glass plate in front of the camera lens, figure 1. Smooth rotation of this plate around some axis in its plane leads to continuous optical displacement of the object image to be recorded. The image distortion may be neglected, if magnitude of the rotation is small. The image displacement direction is evidently orthogonal to the plate rotation axis. This approach helps to achieve maximal fringe contrast, if interferogram visualization is done in the real time mode. Note, that the required direction of the compensated rigid body displacements is often known beforehand. In particular, this is true for the case of tensile testing of samples with a stress concentrator described above.

The following experiment demonstrates potentials of the above-described procedures to compensate for rigid body displacements. As before, a plate rotating in its plane was taken as the experimental object. However, here its center of rotation was outside (to the left of) the picture area to
be recorded. Figure 4a shows initial speckle interferogram of field $U$. One can easily see the border of speckle pattern decorrelation as a circular arch. Figure 4b demonstrates the result of one-pixel computer-assisted displacement of the subtracted picture area along the horizontal axis. As seen, the zone of acceptable fringe contrast makes a stick-slip movement to the right. However, we managed to have an interferogram with a high fringe contrast at the entire observation area using the smooth optical compensation procedure, figure 4c. One might say that the plate rotation axis was conventionally moved to the center of the picture area due to the optical compensation, while it was located outside (to the left or right of) the picture area in both example interferograms obtained by computer-assisted image displacement.

![Diagram](image)

**Figure 3.** (a) Rotation of the test object in its plane, and (b)-(e) speckle pattern interferograms of horizontal $U$ (left) and vertical $V$ (right) displacements at a small (upper) and a large (bottom) angle $\Omega$.

Note that in practice combination of both approaches may be reasonable. The computer-assisted one-pixel shift of subtrahend picture areas is used for rough compensation, while the optical shift is done only within the pixel physical size and serves to visualize interferograms with a maximal possible fringe contrast.

In conclusion, let us demonstrate capacity of optical compensation for rigid body displacement as an actual experiment. A beam with a stress concentrator as a V-notch was tested. The beam was loaded according three-point bending scheme, figure 5a. The concentrator zone of interest was shifted vertically. Under the condition of no displacement compensation in-plane displacement fringes rapidly lost contrast with increase in load. When the sample deflection arrow reached $\sim 30$ microns, it became impossible to obtain any information about local deformation, figures 5b, c. However, compensation...
for rigid body displacements helped to obtain high quality interferograms of local deformations in the concentrator zone, figures 5d, e.

One should mention the existence of the upper limit of rigid body displacements fit for compensation by this approach. This upper limit is due to defects of optical elements that lead to appearance of parasite local phase variations in illuminating beams. A series of special tests using optical elements of rather poor quality gave satisfactory results with rigid body displacements reaching ~300 microns, i.e. several-fold greater than average speckle size.

Figure 4. (a) Initial interferogram of horizontal displacements U with the object rotation center placed to the left of the observation area, and results of discrete computer-based (b) and smooth optical (c) compensation for rigid body displacements

Figure 5. (a) Arrangement of three-point bending of a beam with a stress compensator, and pair interferograms of horizontal U and vertical V displacements: (b, c) initial, (d, e) after compensation for rigid body displacements

The described approach seems helpful in development of special-purpose measurement ESPI-systems as components of test equipment sets intended to study mechanical properties of materials.

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References
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