Draft SPOTS Standard Part III (7)

CALIBRATION
AND ASSESSMENT
OF OPTICAL STRAIN
MEASUREMENTS

Good Practice Guide to Electronic Speckle Pattern Interferometry for Displacement / Strain Analysis

December 2005

1. Scope

Electronic Speckle-Pattern-Interferometry (ESPI) is a technique of experimental full field and non-contact displacement measurement and strain analysis. It is also known under the name Digital Speckle-Pattern-Interferometry (DSPI) or TV-Holography.

ESPI employs coherent laser illumination on the specimen and monitors the change of intensity pattern with a CDD camera. It provides full-field information about 3D-displacement vectors when the specimen is illuminated from different directions. The displacement fields are numerically differentiated in order to obtain strain maps. From the physical point of view Electronic Speckle-Pattern-Interferometry is based on monochromatic laser light illumination, use of a CCD camera, the superposition of two coherent beams on the CCD and the change of the optical phase between the two beams due to displacements.

2. Reference materials

ISO Norms

ISO 11145:2001 Optical instruments – Lasers and laser-related equipment – Vocabulary and symbols.

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ASTM Standards

E 2208-02 Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems

……..

3. Symbols and abbreviations

Symbol	Definition	Units
λ	Wavelength of light	m
Ψ	Optical phase (stochastic)	rad
$\Delta\phi$	Optical phase shift due to change of displacement	rad
$\vec{e}_{Illu}$	unit vector of the illumination beam	1
$\vec{e}_{Obs}$	unit vector of the observation beam	1
$\vec{d}$	displacement on the surface	m
I	intensity of light	Wm^{-2}
I_{ob}	intensity of the object beam	Wm^{-2}
I_{ref}	intensity of the reference beam	Wm^{-2}
i, j	number of pixel of CCD camera	
$\vec{S}$	sensitivity vector of the optical set-up	m^{-1}
$\vec{S}_1(i,j), \vec{S}_2(i,j),...$	$\vec{S}$ for the configuration (optical set-up) 1, 2,..	m^{-1}
u	displacement in x direction	m
v	displacement in y direction	m
w	displacement in z direction	m

Abbreviations

CCD	Charge Coupled Device
ESPI	Electronic Speckle Pattern Interferometry

FFT	Fast Fourier Transform

4. Terminology

Out-of-plane	direction perpendicular to a surface
In-plane	direction parallel to the surface

5. Principles of the method

Electronic Speckle Pattern Interferometry (ESPI) uses coherent light as a measurement tool for deformation measurement. The measurement of the deformation is scaled by the wavelength λ of the laser light.

A monochromatic laser light illuminates an object. The diffuse reflected light from the rough surface is focused in the image plane of a video camera and converted into a grey value field and recorded as an image. The granular appearance of this image is the speckle pattern. A speckle is an interference effect of light which is scattered from a rough surface. The speckle distribution is a "finger print" of the laser illuminated surface

In the case of speckle interferometry an addition of a second reference illumination is necessary In the case of an out-of-plane set-up the laser beam is split into an object beam and a reference beam. The reference beam illuminates the chip directly. On the chip the reference beam and the diffuse reflected light of the object beam interfere. In the case of an in-plane set-up the laser beam is split into two object beams. On the chip the diffuse reflected light from both object beams is interfering. One diffuse reflected beam can be considered as the reference beam. A deformation of the object creates a change in the optical path length of the reflected object beam. The change of optical path length results in the change ΔΦ of the relative optical phase of the two beams and therefore changes the intensity of the speckles. The latter is measured with the CCD camera.

The intensity at a pixel of the CCD camera is [1]

$$I(i,j) = I_{ob}(i,j) + I_{ref}(i,j) + 2\sqrt{I_{ob}(i,j) + I_{ref}(i,j)} \bullet \cos\left(\Psi(i,j) + \Delta\phi(i,j)\right) \qquad (1)$$

where $I(i,j)$ is the intensity at the pixel (*i,j*), I_{ob} and I_{ref} are the intensities of the object beam and the reference beam, Ψ is the mutual, stochastic phase between the reference and the object beam and $\Delta\phi$ is the optical phase change due to the change of deformation

The change of the optical phase $\Delta\phi$ is given by [2]

$$\Delta\phi(i,j) = \vec{d}(i,j) \circ \vec{S}(i,j) \qquad (2)$$

$$\vec{d}(i,j) = \begin{pmatrix} u(i,j) \\ v(i,j) \\ w(i,j) \end{pmatrix} \qquad (3)$$

$$\vec{S}(i,j) = \frac{2\pi}{\lambda}\left[\vec{e}_{Obs}(i,j) - \vec{e}_{Illu}(i,j)\right] \qquad (4)$$

$\vec{d}$ is the displacement on the surface of the object at on the point focused onto the pixel (i,j), $\vec{S}$ is the sensitivity vector of the optical set-up, which is determined by the illuminating point, the point on the object and by the observation point. $\vec{e}_{Illu}$ and $\vec{e}_{Obs}$ are the unit vectors in the directions of the illumination beam and the observation beam respectively. The displacement vector $\vec{d}$ cannot be calculated from the measured intensity I(i,j) for the following reasons:

a) The mutual, stochastic phase Ψ is unknown
b) The three-dimensional displacement vector $\vec{d}$ cannot be determined from the scalar product (2).

The measurement of the full displacement vector $\vec{d}$ requires a minimum of three sensitivity vectors. Those can be created by three out-of-plane illuminations or a mix of out-of-plane illuminations and in-plane illuminations.

In order to determine the optical phase change $\Delta\phi$ due to the displacement of an object point, a minimum of 4 images with different mutual phases Ψ have to be taken, e.g. applying optical phase shifting. This technique is based on the application of a known phase shift [3], e.g. by changing the optical path length of one beam by a piezo actuator. A common method for the phase shift is the 4 + 4 phase shift method. This method uses four images before loading and 4 images after loading, all with a phase shift of 90° between. The change of optical phase is determined as

$$\Delta\phi = \arctan \left. \frac{I_4 - I_2}{I_1 - I_3} \right|_{after\ load} - \arctan \left. \frac{I_4 - I_2}{I_1 - I_3} \right|_{before\ load} \tag{5}$$

Due to the trigonometric function the optical phase $\Delta\phi$ can be only determined as value modulo 2π (wrapped phase). Before the calculation of the displacement the optical phase $\Delta\phi$ has to be unwrapped. The displacement is calculated by solving the equation:

$$\vec{d}(i,j)) = \begin{pmatrix} \Delta\phi_1(i,j) \\ \Delta\phi_2(i,j) \\ \Delta\phi 3(i,j) \end{pmatrix} \circ \begin{pmatrix} \vec{S}_1(i,j) \\ \vec{S}_2(i,j) \\ \vec{S}_3(i,j) \end{pmatrix}^{-1} \tag{6}$$

The elements of the strain tensor $\vec{\varepsilon}$ is calculated from the displacement field as spatial derivatives:

$$\vec{\varepsilon}(i,j)) = \begin{pmatrix} \frac{\partial u(i,j)}{\partial x} & \frac{\partial v(i,j)}{\partial x} & \frac{\partial w(i,j)}{\partial x} \\ \frac{\partial u(i,j)}{\partial y} & \frac{\partial v(i,j)}{\partial y} & \frac{\partial w(i,j)}{\partial y} \\ \text{not possible} & \text{not possible} & \text{not possible} \end{pmatrix} \tag{7}$$

In the case of curved objects the slope of the curvature has to be taken into account at every measuring point.

6. Apparatus

The ESPI measuring system consists of the following elements:

- Optical measuring head with
    - a laser

  - optical elements like beam splitter, mirrors, shutters and lenses realising a minimum of three directions of illumination plus a reference beam (3 independent sensitivity vectors)
  - a CCD camera
- A control and evaluation unit

In Figure 1 the optical design of an ESPI sensor with out-of-plane sensitivity together is shown with the sensitivity vector, the illumination and observation direction and the displacement vector. Figure 2 shows a possible set-up of a 3D-ESPI measuring head.

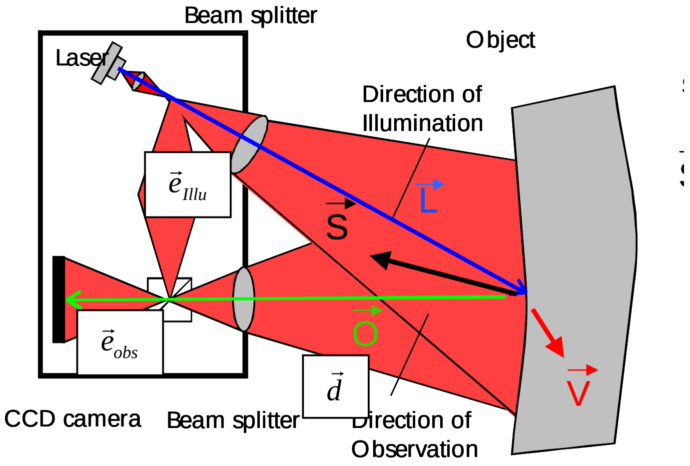

Figure 1: Scheme of an out-of-plane sensor

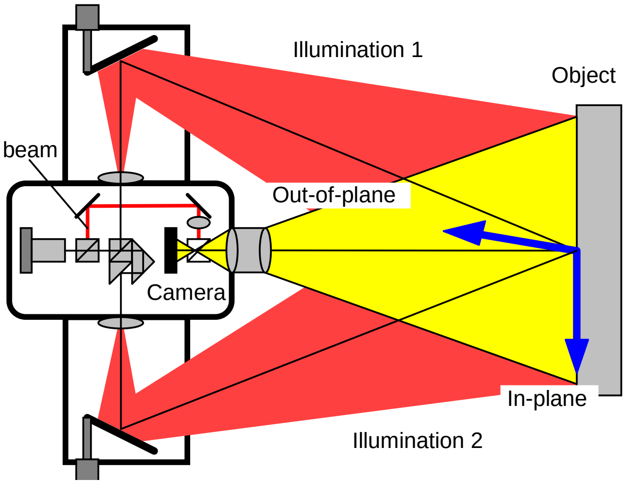

Figure 2: Scheme of an out-of-plane + in-plane sensor

7. Sample preparation

The surface of the sample has to be rough in order to create a diffuse scattered laser beam. The roughness r_a should be larger than $\lambda/4$. In the case of too low a roughness, a highly reflecting surface or a transparent object, a paint or powder has to be applied to the surface under investigation. It must be ensured that the layer will deform like the underlying surface.

8. Calibration procedure

Prior to the measurement, the sensitivity vectors and the magnification of the optics should be known or determined.

The calibration of the optical magnification is done by taking an image of an object of known dimension in the focal plane of the camera, and associating the pixels on the camera to appropriate points on the object.

The sensitivity vectors can be determined, if the illuminating points, the observation directions and the surface coordinates of the object points are known.

The verification of these settings can be achieved experimentally by a calibration specimen of known geometry such as a turntable under rotation, a beam subject to four-point bending, a disc subject to compression across a diameter, or a tensile strip. The exact circumstances of the component test must be reproduced, including temperature, frequency and coating thickness - as well as material properties.

9. Recording and measurement procedures

The measurement procedure for the ESPI system consists of the following steps:

1. Preparation of the sample if necessary
2. Attachment of the sample to the load unit
3. Alignment of the optical system. The optical system should be perpendicular to the surface of the sample.
4. The target area on the sample must be selected by using the imaging system. The samples should be placed in the focal plane.
5. Ensure that no unforeseen relative movement of the sensor with respect to the sample occurs. Avoid vibrations.
6. The magnification of the imaging system and the sensitivity of the set-up should be determined.
7. Identify the area of interest.
8. Adjust the intensity of the laser light illumination for all illumination directions, no saturation on the CCD should occur.
9. Check for good contrast of fringes.
10. Run the measurement. Ensure that the fringe density is not to high, (e.g. that maximal displacement is below the maximal measuring range).
11. Evaluate the data.

10. Data processing procedures

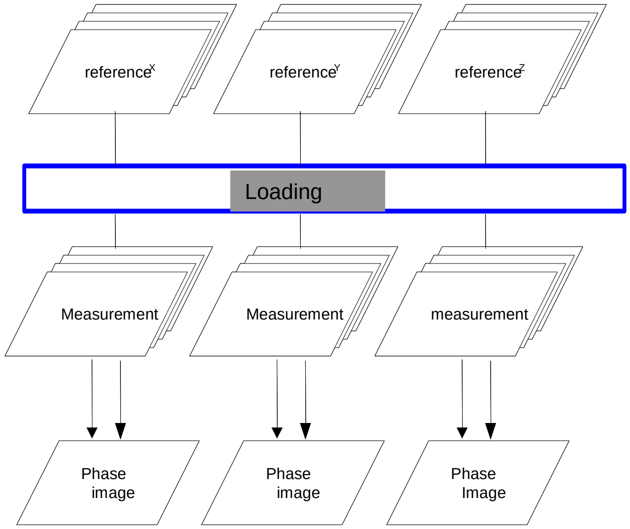

Figure 3: Step 1: Measurement steps from reference to phase maps

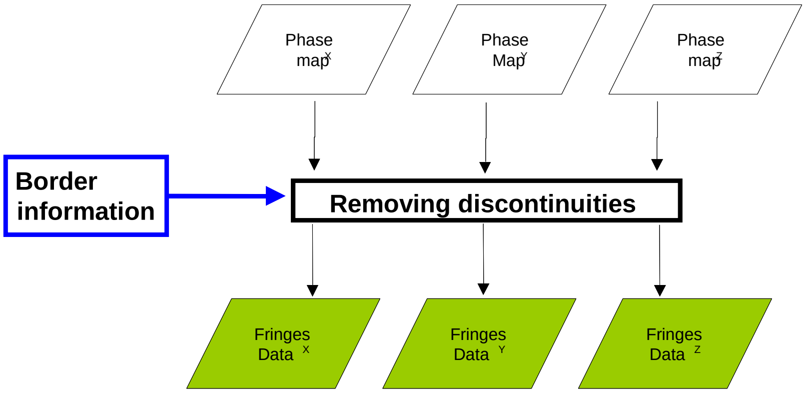

Figure 4: Step 2: Data analysis for the wrapped phase map to the unwrapped phase map

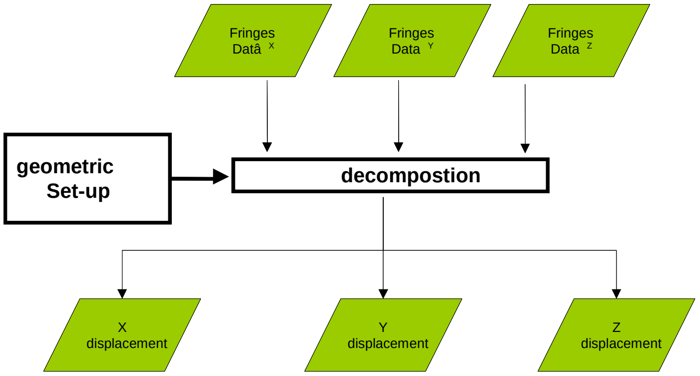

Figure 5: Step 3: Calculation of displacement fields from the unwrapped phase maps

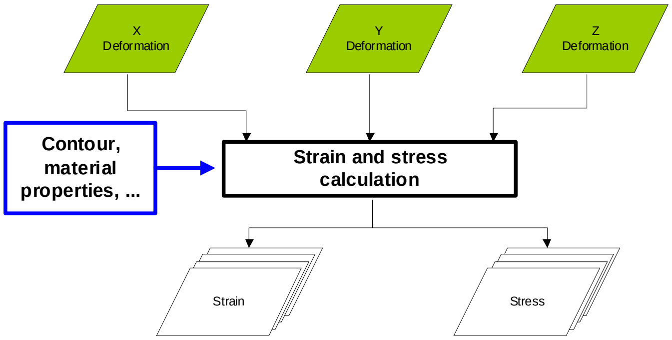

Figure 6: Step 4: Calculation of the strain and stress field from the displacement fields.

11. Areas of applications

The Electronic Speckle Pattern Interferometry is used in various areas or applications. The following list shows a few examples

- Material testing – mechanical and thermo-mechanical behaviour (metal, ceramic, plastic, reinforced material, composite material)
- Component testing (automotive, aerospace, medical, electronical…)
- Defect recognition
- Failure analysis
- …

12. Bibliography

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1. Kreis, T., *Handbook of holographic interferometry: optical and digital methods*, p 402ff., ISBN 3-527-40546-1. Wiley-VCH, Weinheim : 2005
2. *Ibid*., p 193ff., p 402ff.
3. Rastogi, P. K., *Holographic Interferometry*, p 60ff., ISBN 3-540-57354-2, Springer Series in Optical Sciences, Berlin, 1994