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Application of the ESPI method for chassis frame's element displacement determination

1. Introduction

The ESPI method is a type of speckle interferometry which utilizes electronic data processing and data analysis. In a typical ESPI measurement system, speckle patterns are recorded by a video or digital camera and further analysis and data processing is carried out by electronic means, either analogue or digital [1], [3].

ESPI can be used in measurement of displacement distribution as an alternative to speckle photography or holographic interferometry, especially in cases where information about every component of a displacement vector on the surface of an object is needed. The ESPI method can be used for displacement measurements in static load conditions, as well as for measurements of vibrations or – using pulse laser – for measurements in dynamic load conditions (including impact). Compared to traditional speckle interferometry, the ESPI method has the following advantages:

- sensitivity of digital cameras is usually higher than that of holographic plates or films, and because of that shorter exposure times can be used for recording speckle patterns. Shorter exposure times means that a measurement can be done despite poor vibration isolation;
- measurement costs are significantly lower, because consumption of photographic materials (plates, films) is not necessary;
- electronic data processing is very fast and in many cases allows real time measurements and displacement distribution visualisation;
- modern ESPI systems can be used in the presence of another sources of light, which means that measurements can be carried out not only in a dark room (it makes measurements much easier);
- small dimensions of modern CCD cameras allows to develop small, portable measurement systems. By using optical waveguides, it is also possible to carry out measurements in areas that are not easily accessible.

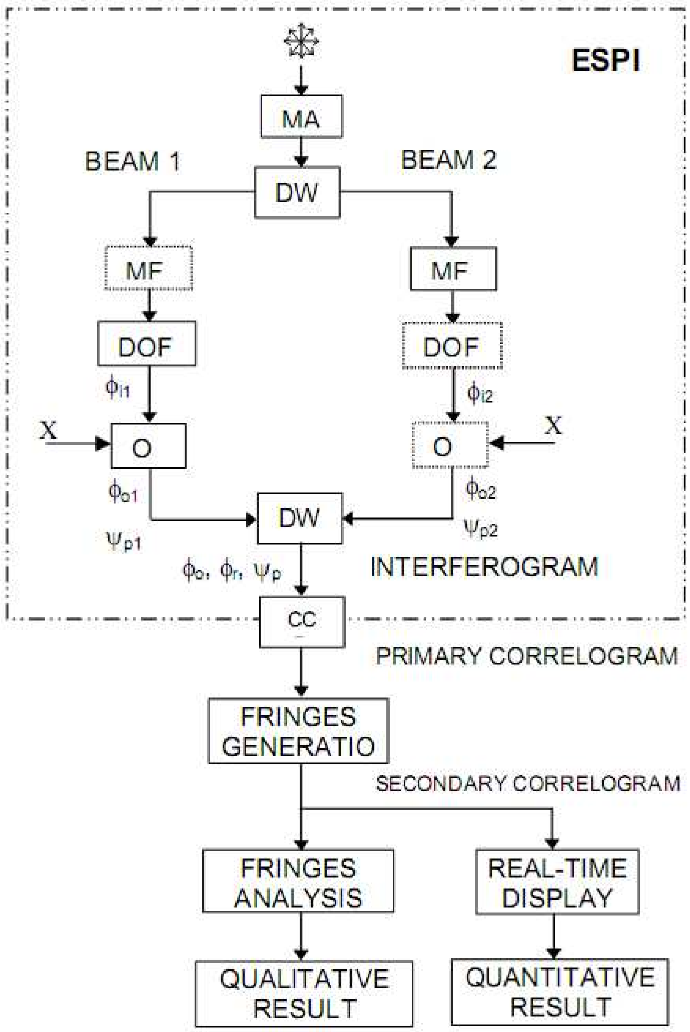
Naturally, the ESPI method also has some disadvantages:

- spatial resolution of CCD cameras is lower than that of holographic plates or films. It means that part of a details is lost, but also because of that the measurement range is limited;

- costs of a measurement system are in almost every case higher than costs of a traditional holographic interferometry or speckle photography system.

2. Measurement set-up

A measurement ESPI set-up consists of two parts: an optical part (in which speckle pattern is generated) and an electronic one (in which a speckle pattern is converted to a digital data set, correlation fringes are generated and analysed) – Fig. 1.



MA – amplitude modulator
DW – beam splitter
MF – phase modulator
DOF – speckle de-correlating device
OB – object
CCD – camera

ϕ_{i1}, ϕ_{i2} – phase of light wave generated by laser in beam 1 and 2

X_1, X_2 – measured value in beam 1 and 2

ϕ_{o1}, ϕ_{o2} – phase of light wave after reflection from the surface of measured and standardised object

ψ_{p1}, ψ_{p2} – phase of speckle depending on the roughness of surface of measured and standardised object

ϕ_o – phase of light wave which is the result of interference of beam 1 and 2

ϕ_r – change of phase which is the result of wave propagation form laser light source to camera

ψ_p – phase of speckle on the pattern which is the result of interference of beam 1 and 2

Fig. 1 Scheme of optical and electronic parts of ESPI measurement system

The optical part of a set-up consists of a speckle interferometer (shown in Fig. 3). In the optical part of a set-up, mostly two-beam interferometers are used, however some multiple-beam systems also exist. In an optical interferometer, a coherent laser light beam is divided into two parts (using optical elements called beam-splitters). One of the beams is reflected by the surface of the measured object (object beam), whereas the second is unchanged or reflected by the standardized object (reference beam). Both beams are directed to the same plane, where they are combined. Combination of the two beams is recorded by a CCD camera.

3. Measurement process

The measurement process consists of 4 stages: the first and second stage proceeds in the optical part of set-up, the third and fourth in the electronic part. The first stage consists in generation of a speckle interferogram connected to the illuminated surface. Input signals are in that case ϕ_{i1}, ϕ_{i2} – phase of light wave generated by the laser in beam 1 and 2, and X_1, X_2 – the measurand in beam 1 and 2. The output signal is a speckle pattern (interferogram) which is the result of interference of the waves in beam 1 and 2 (Fig. 2b).

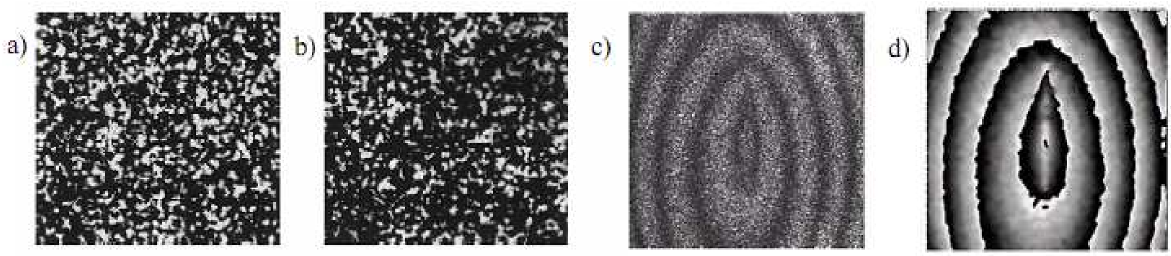


Fig. 2 Speckle pattern (a), primary correlogram (b), secondary correlogram (c) and phase map (d)

The most important parameter of this pattern is the phase of speckle in pattern ψ_p. The second stage of the process is connected with recording of a speckle pattern by the light-sensitive element of the camera. The output signal by means of a digital image is called a primary correlogram. In the primary correlogram, information about measurand distribution (by means of speckle brightness) is stored, however this information is embedded in the random speckle pattern. The third stage is generation of a secondary correlogram (by means of a fringe pattern) with visible changes of average intensity. Fringes can be displayed and analyzed to obtain a quantitative result (Fig. 2c). The fourth stage is digital analysis of a fringe pattern and the information about values of measurand.

A raw result of this stage is a phase map, while the final result is a file consisting of data describing the distribution of measurand value (Fig. 2d).

First stage of measurement means generation of a speckle pattern and an interferogram. At this point, the most important issues during that stage should be mentioned:

- every displacement of object surface as well as every change of illumination or observation conditions triggers a change of the speckles phase,
- the result of interference of the speckle pattern from beam 1 (object one) with beam 2 (reference one) or with reference speckle pattern is the difference of phase of speckles consisting object speckle pattern beam 1 and phase of beam 2 or phase of speckles in the reference pattern.

Figure 3 shows the schemes of typical optical set-ups of speckle interferometers used in the ESPI method for recording in-plane or out-of-plane displacement distributions (displacements parallel or perpendicular to the plane of recording – plane of image generation in recording camera).

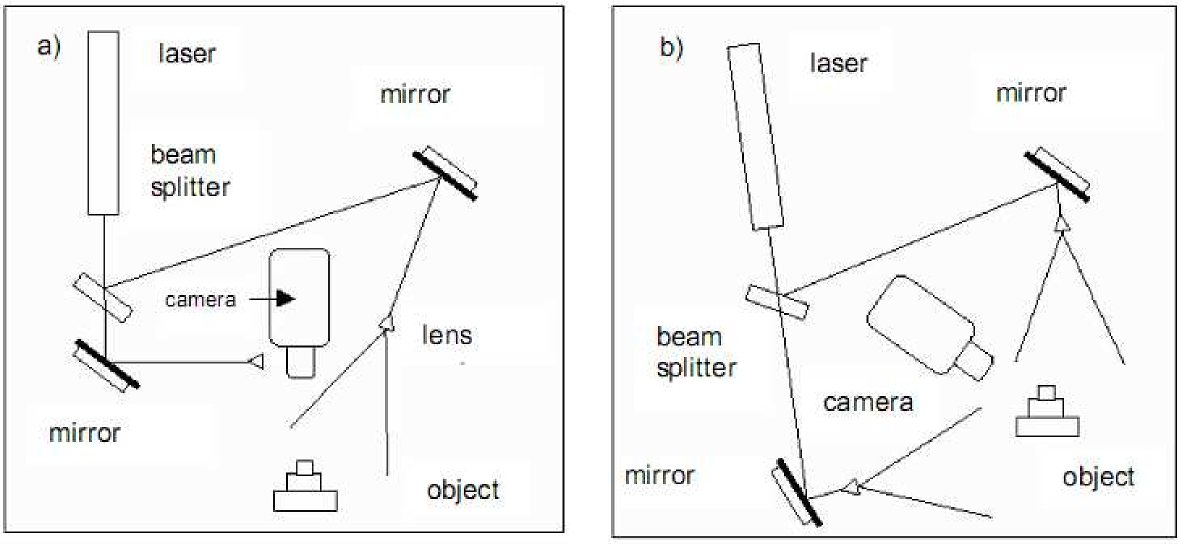


Fig. 3 Optical set-ups of interferometer for recording out-of-plane (a) and in-plane (b) displacements

In the second stage, recording of two composed light beams by a camera proceeds. The output signal from the camera is the result of exposure of the camera's sensitive element during recording of a single frame. In the case of object dynamic loading as well as in the case of amplitude or phase modulation during frame recording, the output signal will be the result of recording of a variable intensity beam. Time of single frame recording influences the way the difference of optical wave phases connected to measurand is stored in the output signal.

Intensity of light is averaged by camera recording by means of spatial averaging on every pixel area as well as temporal averaging during time of frame recording. An image, which is the result of that averaging is a primary correlogram. Various camera parameters (sensitivity to laser light, camera reading constant, normalized exposure weight function, etc.) can influence the generation of a secondary correlogram.

The obtained correlogram is proceeded by further digital analysis. Fringe pattern and secondary correlogram are obtained in two steps. In the first step, local changes of light intensity in every speckle are converted into variations of contrast of speckles. In the second stage, square-law demodulation is applied to transform local changes in contrast into secondary fringes of mean brightness.

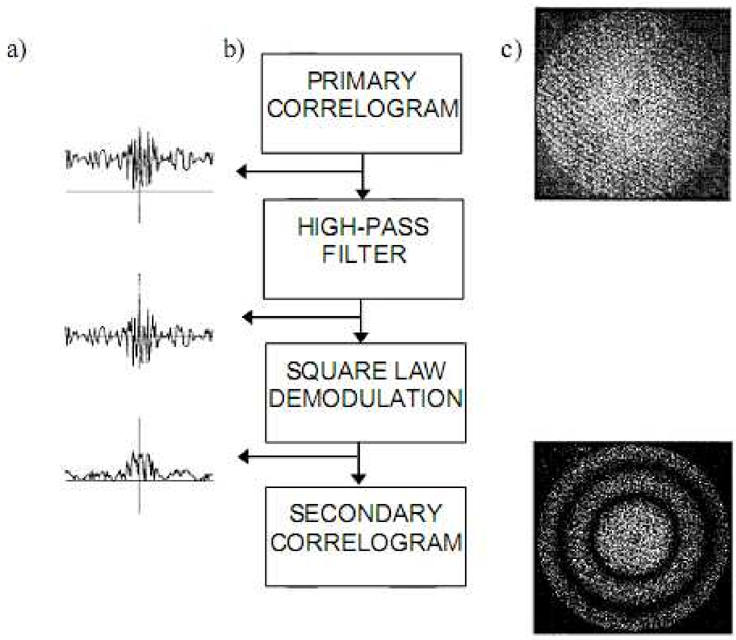


Fig. 4 Scheme of fringe patterns generation from primary correlogram a) distribution of light intensity along line A-A, b) block diagram, c) speckle images

Automatic analysis of obtained results consists of the following steps:

- phase evaluation – this step is the calculation of spatial distribution of pattern phase. The output of this step is an array of values of phase corresponding to measurand and it is called a phase map;
- phase unwrapping – this step involves change of the phase map into an unwrapped array of phase map, without any discontinuities on the fringes;

- removal of additional stage – during the fringe generation process and data evaluation some terms not related to the measurand may be added to the phase pattern. However, these terms are constant or linearly dependent on spatial co-ordinates and can be removed. In this step, it is carried out mostly using estimation by least-squares fitting;
- re-scalling – in this stage the final set of data is obtained by calculation of measurand values based on the phase values.

4. Measurements of every component of displacement vector

Combination or multiplying of optical set-ups presented in Fig. 3 allows to measure each of the three components of a displacement vector. Mostly, displacement components are recorded in the step-by-step procedure. A typical optical set-up of a measurement head for recording displacements in the three perpendicular directions is shown in Fig. 5.

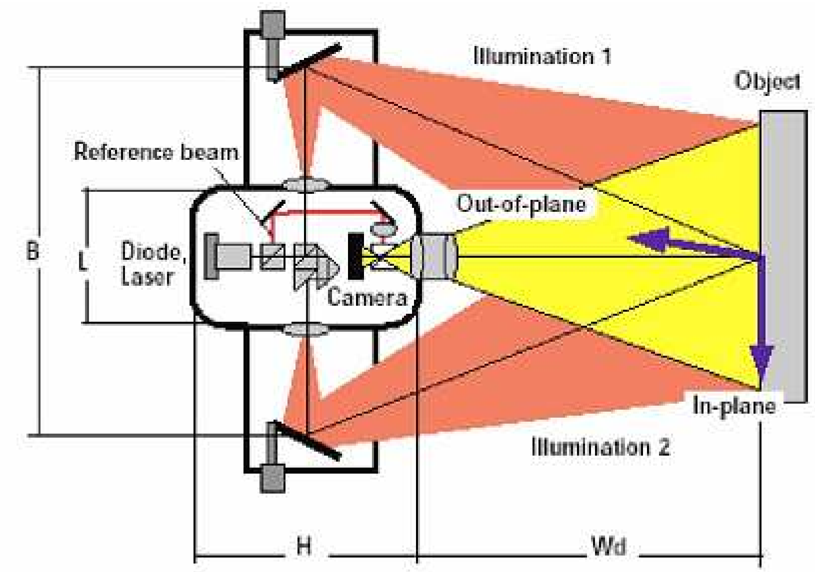


Fig. 5 Optical set-up of measurement head for recording three displacement vector components

6. Summary

Modern experimental mechanics of solids, more than ever, use full-field optical methods for stress, strain and displacement analysis [2]. Many significant advantages of these methods make them valuable, easy-to-use and practical methods. The ESPI method combines all the advantages of traditional optical methods with modern, automatic data processing. Because of that, the ESPI method becomes one of the most important methods of displacement analysis.

References

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[2] G. Restivo & G.L. Cloud, *Embedded Digital Speckle Pattern Interferometry for Three-dimensional Strain Analysis*, Experimental Mechanics 48, 731–740, 2008

[3] Ole Lekberg, *Electronic Speckle Pattern Interferometry*, Phys. Technol., 1, 16 – 20, 1890