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SENSOR FOR IN-PLANE DISPLACEMENT MEASUREMENT BASED ON COMBINED GRATING AND SPECKLE PATTERN PHASE SHIFTING INTERFEROMETRY

Dariusz Łukaszewski, Leszek Sałbut
Warsaw University of Technology, Institute of Micromechanics and Photonics, Warsaw, Poland
e-mail: d.lukaszewski@mchtr.pw.edu.pl

The aim of this paper is to present a novel concept of an in-plane displacement sensor head based on grating interferometry (GI) and digital speckle pattern interferometry (DSPI) methods as complementary ones in a single device. The ultimate aim of this is to show new directions of development of microsensors for experimental mechanics purposes. In the paper, complete designs of sensor heads along with tolerance calculation required for prototyping are considered and analyzed. Their advantages are pointed out depending on application. Also theoretical analysis of the state of polarization in a cavity sensor are performed and a polarization phase shifting method for automatic fringe pattern analysis is shown. Finally, the technology demonstrators of the designed sensor head and possible directions for their further development along with a proposal of replication are presented.

Key words: grating interferometry, digital speckle pattern interferometry, interferometric sensor head

1. Introduction

In-plane displacement measurements are used for wide variety of objects (i.e. measurements of mechanical elements, monitoring of crucial points of constructions or, in general, of engineering structures). The data from the measured object/structure should be easy to acquire and process, so the user can asses the state of the object in short time and schedule necessary maintenance in order to prevent accidences (Egawa, 1997).

The most common systems used are based on electrical-resistance strain gauges (Dally and Riley, 1987) because of their linear characteristics and stable behavior. Strain gauges provide information about the average value of displacement from the area of the object covered with them, which is nowadays not always sufficient for further analysis and predictions.

From variety of other methods, one can distinguish interferometry methods, which are used for measurement of in-plane displacement or flaw detection (Kobayashi, 1993; Kreis, 2005; Post, 1987; Ranson *et al.*, 1987) in full field of view with high spatial resolution. Data gathered from mentioned methods can provide general information about the state of the object even before computer processing. Measurement possibilities with usage of coherent optical methods are applied in local and global measurements of different class of objects, where high sensitivity is required. Two main optical methods used for such measurements are grating interferometry (GI) (Post, 1987) and digital speckle pattern interferometry (DSPI) (Ranson *et al.*, 1987), however there is lack of miniature systems which can utilize them in outdoor measurements.

Both GI and DSPI have advantages and drawbacks depending on measurement requirements and measuring objects. The main advantage of GI is that successive measurements have their reference at the zero state of the object (moment when object grating was applied), so it provides information about the cumulative displacement between measurement periods. In the case of DSPI, only differential measurements are possible (successive states of the object need to be correlated within the system measurement range), so the system needs to remain on the object in order to grab continuous series of images during measurement. The mentioned requirement constitutes a risk of losing continuity in measurements in the case of interruption caused by a random event, i.e. problems with power supply. On the other hand, speckle pattern interferometry does not require preparation of the surface as long as it scatters light, while grating inteferometry requires application of diffraction grating onto the object surface, which is not always possible. Moreover, diffraction gratings can be applied only on a plane, flat surface – such a requirement limits the number of objects groups, which can be measured.

Considering all mentioned features, it can be stated that both methods are complementary and combination of both techniques into a hybrid solution can provide a system suitable for reasonable monitoring of most crucial points of engineering structures (i.e. welds, cracks, notches).

In the paper, some aspects of design of a hybrid in-plane displacement sensor based on combination of GI and DSPI are described. The authors present that the same interferometric head (Lukaszewski *et al.*, 2010) can be used for realization of GI (when the grating is attached to the plane object under test), DSPI (for objects with scattered surfaces) and GI/DSPI (when the specimen grating is attached only in the part of the object in the field of view). In that last case, the specimen grating is used as the reference. The local data obtained by GI is used for proper scaling of global data obtained by DSPI, even in the case of non-continuous speckle pattern acquisition. Moreover, this method can be used for both, flat and non flat surfaces of the object under test.

The authors also propose a temporal phase shift method (TPS) for automatic fringe pattern analysis (Huntley, 1998). TPS method can be utilized by parallel movement of the mirror in the sensor head by means of PZT. Due to moving elements, such a solution is not optimal especially in a device, which is dedicated for out-door measurements. Here, in order to overcome the mentioned problem, an application of the polarization phase shift method (PPS) is proposed. Such a solution, along with usage of a dynamic wavefront sensor (Millerd *et al.*, 2005), enables elimination of all moving elements from the sensor and analysis of fringe pattern from only one acquired frame. The mentioned idea results in miniaturization of the sensor and desensitization to vibration.

Therefore, in the first part of the paper, short theoretical background for GI and DSPI is presented and the concept of sensor heads along with design is shown.

The following section is devoted to theoretical and experimental analysis of polarization states in cavity sensor heads and realization of the polarization phase shifting method for fringe pattern analysis.

Next, the comparison of the proposed sensor heads is presented and advantages depending on application are pointed out.

In the last part of the paper, the laboratory system for proof of principle along with experimental results is presented.

2. Description of the sensor

The sensor is dedicated for in-plane displacement measurement with usage of two interferometric methods depending on measurement conditions and objects surface. Hybrid measurement gives possibility of using advantages of both grating interferometry and digital speckle pattern interferometry, especially in the case of small areas of objects, crucial points of an engineering structure or MEMS measurement.

The main advantages of the sensor are small dimensions, low sensitivity to vibrations, possibility of low cost replication techniques by means of MEMS silicon technology.

The sensor consists of three main modules: a) high coherent illumination module, b) sensor head and c) detection module (CCD/CMOS camera). The basic scheme of the system is presented in Fig. 1.

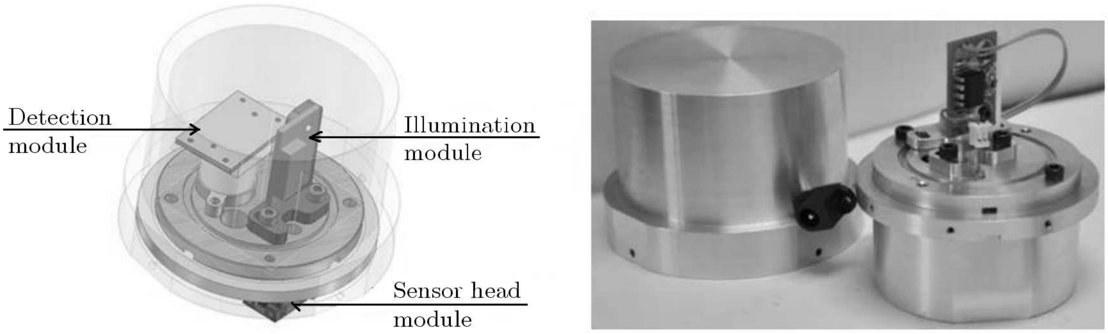

Fig. 1. Basic scheme and photo of the coherent sensor utilizing the hybrid method

The main parameters of the proposed sensor are shown in Table 1.

Table 1. Main parameters of the sensor

Sensor head	Air cavity with glass or silicon elements
Object under test	With diffraction grating applied or with scattering surface
Grating frequency	1200 l/mm
Measurement techniques	GI or DSPI
Field of view	2 mm×2 mm
Measuring range	up to 20 μm
Sensitivity	417 nm/fringe
Resolution	$\sim$ 5 nm
Dimensions	∅60 mm × 115 mm

2.1. Theoretical background of Grating Interferometry (GI)

Grating Interferometry (GI) or Moiré interferometry is used for measurements of in-plane displacement of flat objects under test. The principle of the method is shown in Fig. 2.

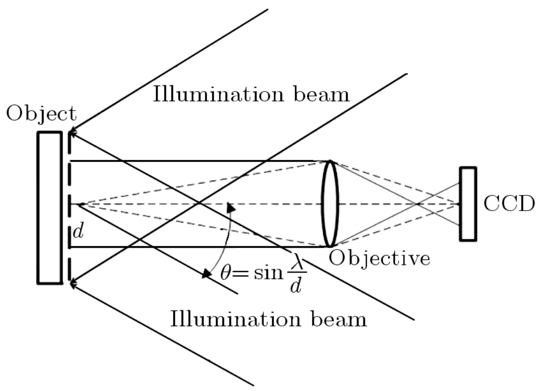

Fig. 2. Principles of grating inteferometry for in-plane displacement measurement

The area of interest of the measured object needs to be covered with high frequency diffraction grating (object grating), which is the element sensitive for displacement. The object grating is illuminated with symmetrical laser beams with plane wavefronts. Incident angles of these beams are equal to $+1$ and -1 diffraction angles of the object grating. The diffracted beams propagate coaxially and perpendicularly to the object.

The grating suffers from deformation equally to the object, thus if any load is applied to the object the grating deforms and, as a result, the wavefronts of the incident beams are no longer plane. The deformed wavefronts carry information of in-plane displacement of the object (Post, 1987). The complex amplitudes of beams can be described by the following equations (Patorski and Kujawinska, 1993)

$$E_{+1} = \exp\Big\{\mathrm{i}\Big[\frac{2\pi}{d}u(x,y) - \frac{2\pi}{\lambda}w'(x,y)\Big]\Big\} \qquad E_{-1} = \exp\Big\{-\mathrm{i}\Big[\frac{2\pi}{d}u(x,y) + \frac{2\pi}{\lambda}w'(x,y)\Big]\Big\} \tag{2.1}$$

where d is the grating period, $u(x,y)$ is the in-plane displacement perpendicular to object grating lines, λ is the wavelength, $w'(x,y) = w(x,y)(1+\cos\theta)$ is the out-of-plane displacement and θ is the angle of diffraction of $+1$, -1 diffraction angles.

As the effect of interference, one can obtain the intensity distribution as follows (in the case of normalized amplitudes)

$$I(x,y) = 2\Big[1 + \cos\frac{4\pi}{d}u(x,y)\Big] \tag{2.2}$$

The intensity distribution depends on the in-plane but does not depend on the out-of-plane displacement.

2.2. Theoretical background of Digital Speckle Pattern Interferometry (DSPI)

Speckle pattern interferometry is widely used for displacement measurements of rough surfaces. As distinct from other interferometric methods, information is coded in a speckle pattern instead of a fringe pattern. The speckle effect appear on a rough surface, which is illuminated with highly coherent light. Speckles are the result of interference of waves scattered on the measured surface (Jones, Wykes 1989).

In order to obtain information about displacement values, the speckle pattern from successive object states needs to be correlated. The frame from the reference state is subtracted (or added) from the measuring state frame, fringes created by this operation are called correlation fringes and carry information about displacement of the object. The correlation fringes can be processed with usage of standard automatic fringe pattern analysis (AFPA) methods (Robinson, 1993). The main drawback of correlation fringes is a high level of noise which needs to be filtered before further processing and a low level of contrast. Exemplary speckle patterns and correlation fringes are shown in Fig. 3.

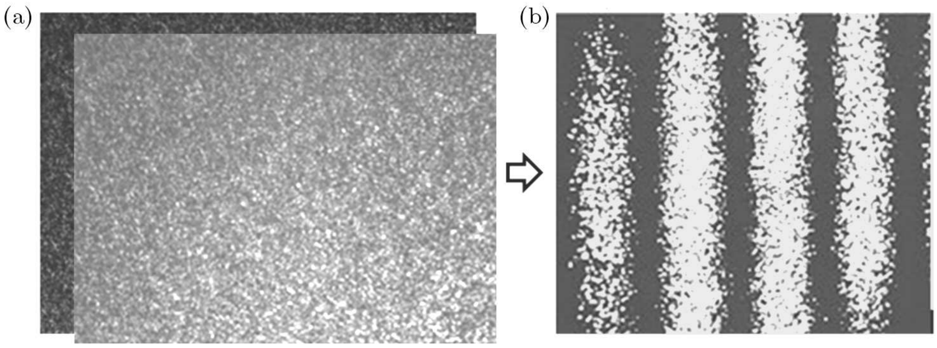

Fig. 3. (a) Exemplary speckle patterns and (b) correlation fringes

As for grating interferometry, in order to measure in-plane displacement with speckle pattern interferometry, symmetrical illumination needs to be provided (Sirohi, 1993). The change of phase caused by deformation of the object is described by equation

$$\Delta\phi(x,y) = \frac{4\pi}{\lambda} u(x,y) \sin\theta \tag{2.3}$$

where $\Delta\phi(x,y)$ is the change of phase, λ is the wavelength, $u(x,y)$ is the in-plane displacement and θ is the angle of illuminating beams.

The basic system for such measurements is shown in Fig. 4.

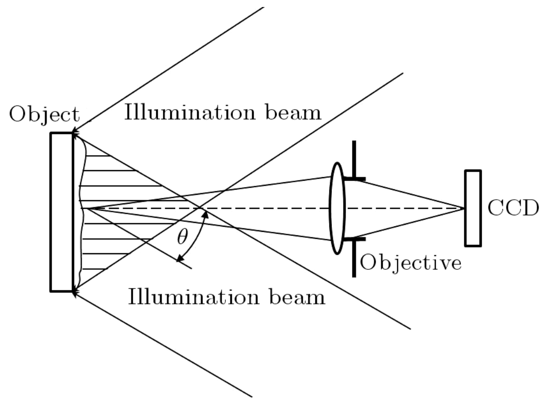

Fig. 4. Basic ESPI system for in-plane displacement measurement

The maximum displacement, which is possible to measure, is limited by the speckle size and detector pixel size (Jones and Wykes, 1989). In the case when θ is equal to λ/d, the same optomechanical sensor design as for GI can be used.

2.3. Proposed sensor heads

The concept of the sensor head is based on air cavity, free space propagation waveguide. Major components of the sensor head are: (RG) reference linear diffraction grating, (S) glass spacer and (RS) reflective glass or silicon surfaces. Reference grating is illuminated by a collimated laser beam and creates symmetrical illumination (usage of $+1$ and -1 diffraction angels). Diffracted beams are reflected by mirrors which create air cavity (free space beam propagation) and illuminate the object.

In the paper, two types of designed heads are presented. One with the same number of reflections for both interfering beams (A) and the second with a different number of reflections for each interfering beam (B). Head (A) uses both diffracted illumination beam, while head (B) uses only one diffraction order (symmetrical illumination is maintained by reflection of half of the diffracted beam aperture from the perpendicular mirror). The sensor heads are presented in Fig. 5.

The mechanical design of the sensor head module is dedicated for both types of sensor heads.

There are few crucial elements if it comes to design of the head. In order to achieve proper symmetrical illumination, the sensor head dimensions along with tolerance need to be calculated depending on the reference grating period, wavelength and beam diameter. Analysis shows that the most crucial sensor head parameters are its height (H) and length (L) marked in Fig. 6.

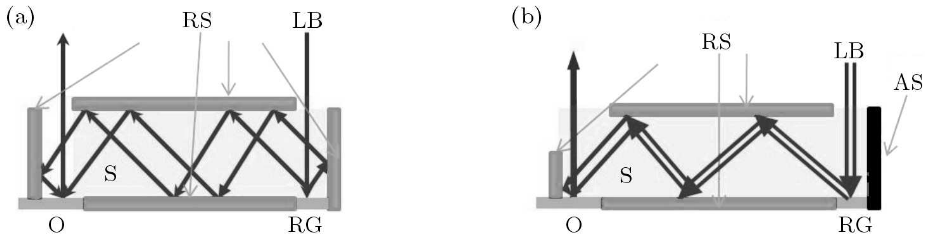

Fig. 5. Proposed sensor heads (a) with equal number of reflections of both interfering beams – (A) and (b) with different number of reflections of each interfering beams – (B); RS – reflective surface, LB – laser beam, AS – absorbing surface, RG – reference grating, O – Object, S – Spacer

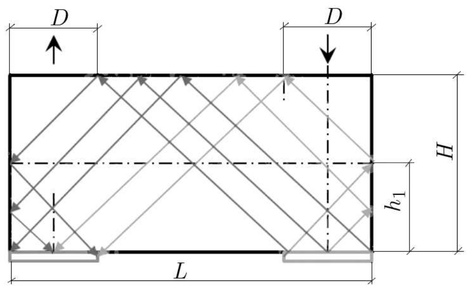

Fig. 6. Crucial parameters of the sensor head (Lukaszewski *et al.*, 2010)

Some exemplary parameters calculated for different wavelengths are presented in Table 2.

Table 2. Geometrical parameters of sensor head

Wavelength	nm	532	593	671
Diffraction grating frequency	lines/mm	1200	1200	1200
Refractive index	–	1	1	1
Reflection angle	deg	39.67	45.36	53.63
Used beam diameter	mm	2.4	2.4	2.4
Number of reflections from top surface	–	2	2	2
Length (L)	mm	16	16	16
Height (H)	mm	3.32	4.05	5.43

3. Implementation of polarization phase shifting method

The presented sensor heads utilize waveguide concept. During propagation, the illumination beam suffers from numerous reflections from materials (aluminum or silicon), which can affect its polarization. The theoretical analysis of changes of the polarization state were performed in order to check if the mentioned changes affect the contrast of interference and to find the optimum input state of polarization.

In the analysis, both proposed designs of heads were considered.

In order to simplify calculations, some major assumptions were made before further analysis:

- Linear polarization of the input beam (most of commonly used lasers have at least 100:1 ratio, which is linear from the detectors point of view).
- There is no depolarization on all surfaces.

On these assumptions further calculations were performed accordingly to the Jones notation (Born and Wolf, 1999) and Fresnel equations (Born and Wolf, 1999).

In the case of the sensor head (A), there is the same number of reflections for every beam, and they both suffer equally from polarization changes. The output polarization of the beam is different than the input one, but it is in phase for both beams and the contrast of interference fringes is constant. From that, one can deduce that the polarization adjustment of illumination source is not required in the sensor with such a head.

In the case of the sensor head (B), there is a different number of reflections for each beam, and it does influence the output intensity, which can be noted respectively to the Jones formalism as

$$\begin{aligned} I &= (a_{11}a_{11}^* + b_{11}b_{11}^*)\cos^2\beta + (a_{22}a_{22}^* + b_{22}b_{22}^*)\sin^2\beta \\ &\quad + 2\,\mathrm{Re}\,[(a_{11}b_{11}^*\cos^2\beta + a_{22}b_{22}^*\sin^2\beta)\mathrm{e}^{\mathrm{i}2\phi}] \end{aligned} \tag{3.1}$$

where β is the diagonal angle of polarization, ϕ – phase, and

$$\begin{bmatrix} a_{11} & 0 \\ 0 & a_{22} \end{bmatrix} = \mathbf{J}_{A''} = \mathbf{J}_{SP}\mathbf{J}_A\mathbf{J}_{SO} \qquad \begin{bmatrix} b_{11} & 0 \\ 0 & b_{22} \end{bmatrix}] = \mathbf{J}_{B''} = \mathbf{J}_{SP}\mathbf{J}_B\mathbf{J}_{SO}$$

$\mathbf{J}_b$ and $\mathbf{J}_A$ – Jones matrix for n-numbers of reflection of interfering beams from reflective surfaces (RS), $\mathbf{J}_{SO}$ – Jones matrix for reference grating (RG), $\mathbf{J}_{SP}$ – Jones matrix for the object surface.

The distribution of output contrast of interference fringes from azimuth of input polarization was analyzed for the case of aluminum and silicon reflective surfaces, and are presented in the Fig. 7.

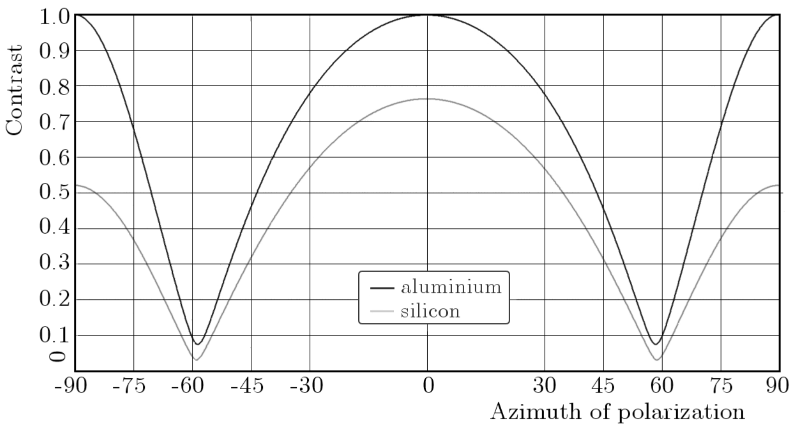

Fig. 7. Changes of output contrast

The presented dependence of contrast from input polarization shows that for linear polarization oriented at an angle ~ 57 degrees, the output beams have orthogonal states of polarization (contrast drops nearly to 0). Such effect makes it possible to apply polarization phase shift (PPS) into the sensor head (B). In order to perform it, one should modify the design and add a quarter waveplate and rotational analyzer as it is shown in Fig. 8.

By using the quarter waveplate, circular polarization of opposite directions is obtained in the output interfering beams. In order to achieve interference between these beams, an analyzer is needed. Rotation of the analyzer introduces phase shift depending on its angle. The intensity distribution in the presented head can be described by the equation

$$I(x,y) = 2\Big\{1 + \cos\Big[\frac{4\pi}{d}u(x,y) + 2\alpha_A\Big]\Big\} \tag{3.2}$$

where $2\alpha_A$ is the change of phase introduced by rotation of the analyzer by an angle equal to α_A.

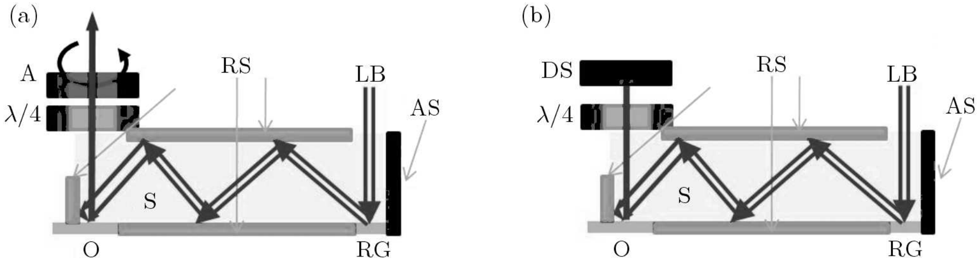

Fig. 8. Polarization phase shift sensor heads: (a) with rotational analyzer and (b) with dynamic wavefront sensor (Patorski and Kujawinska, 1993); RS – reflective surface, LB – laser beam, AS – absorbing surface, RG – reference grating, O – Object, S – Spacer, $\lambda/4$ – quarter waveplate, A – analyzer, DS – dynamic wavefront sensor (Millerd *et al.*, 2005)

The mentioned concept can be modified by usage of a dynamic wavefront sensor (Millerd *et al.*, 2005) as the detector in order to eliminate all moveable elements of the sensor and make it less sensitive to vibration. The dynamic wavefront sensor is a camera in which each pixel is divided into 4 subpixels. Each subpixel is sensitive to different state/azimuth of polarization. Such a solution enables realization of the required phase shift from only one image frame.

4. Experiment – proof of principle

The demonstrative measurements were performed on a specimen presented in Fig. 9a. It was an rectangular plate made of polymethyl methacrylate (PMMA) with arched notch. The sample suffers from 3 point bending, the load was applied via micrometer (absolute displacement between two registered states was 0.04 mm) in the center of the sample. In order to predict possible displacements in the sample caused with the mentioned load, a FEM model was developed and presented in Fig. 9b.

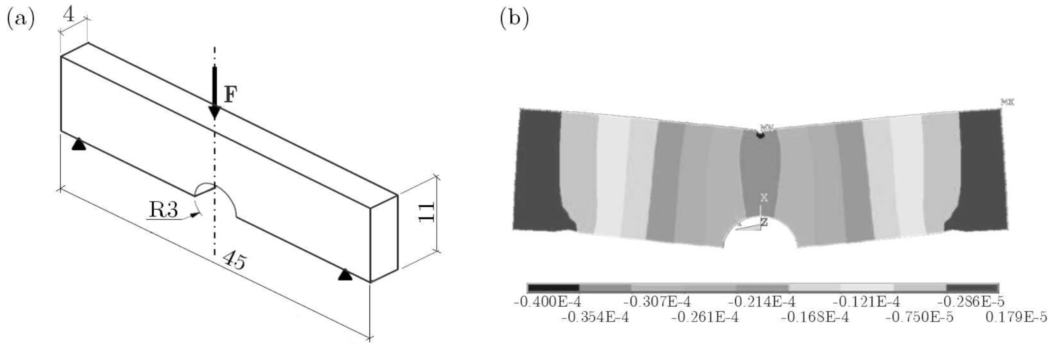

Fig. 9. Specimen used for measurements (a) along with its FEM model (b)

At one side of the sample, linear grating with spatial frequency of 1200 lines/mm was applied, while on the other side it was painted with a scattering paint. The first approach to the measurement was done by means of GI using polarization phase shift (PPS). Phase-shifted interference fringes where gathered for two states of load (Fig. 10b). The second measurement was performed by means of DSPI with the phase shift introduced by a piezo transducer (PZT). The phase-shifted correlation fringes were achieved for the same state of load (Fig. 10c) as it was in the case of GI (note that the marked measuring area was a bit smaller). The approach used for obtaining phase fringes was the phase of differences.

Theoretical analysis proves that PPS is also possible for DSPI mode but, it requires a scattering surface to maintain its state of polarization.

The analysis of fringe patterns was performed with a 5-frame algorithm (Robinson, 1993). Phase maps were scaled to displacement values. The results of performed measurements are presents in Fig. 10d and 10f. The comparison of results achieved from both methods is presented in Fig. 10e.

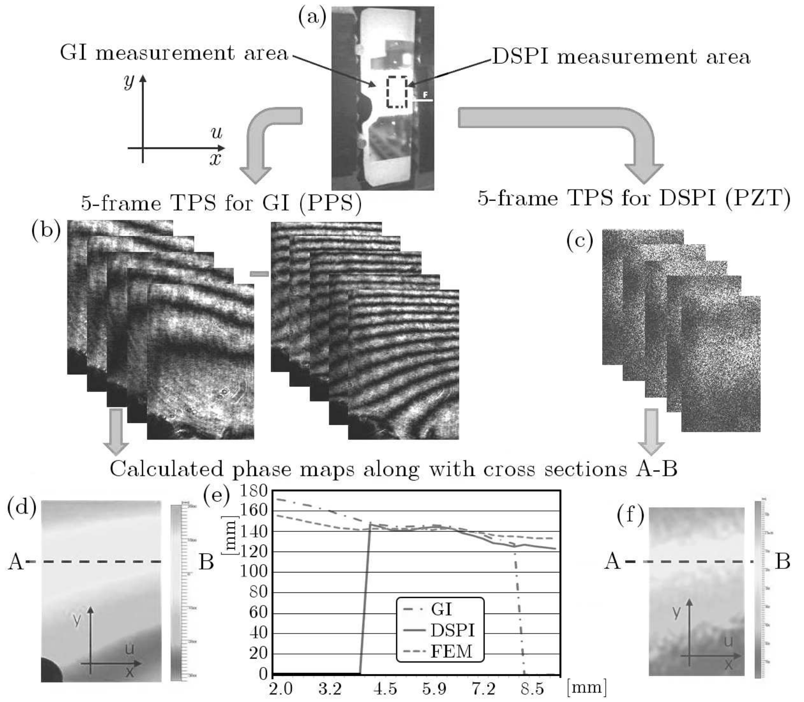

Fig. 10. Results of measurements: (a) specimen, (b) set of phase shifted interference fringes in two subsequent object states for GI mode, (c) set of phase shifted correlation fringes for DSPI mode, displacement maps (d) for GI, (f) for DSPI and (e) cross sections showing absolute values for both modes and FEM model

5. Final conclusion

The presented concept of GI/DSPI air cavity sensors opens new possibilities for full field, in plane displacement measurements purposes. It can be used for tests of industrial components, diagnosis of new materials and composites or monitoring of crucial points in engineering structures. The sensor is characterized by a compact and module based structure.

The authors proposed two types of measuring heads, which can be used with the same main body frame of the sensor. The second sensor head (B) can utilize the polarization temporal phase shift (PPS), which along with usage of the dynamic wavefront sensor (Millerd *et al.*, 2005) enables elimination of all moving elements from the sensor and analysis of fringe pattern from only one acquired frame. Such an idea results in miniaturization of the sensor and desensitization to vibration.

The proof of principle test shows that the same opto-mechanical design can be used for all possible sensor working modes (GI – when the grating is attached to the plane object under test, DSPI – for objects with scattered surfaces and GI/DSPI – when the specimen grating is the reference for DSPI measurements). The proposed combination of methods can be successfully implemented in the final device.

The presented sensor provides a method for investigation of variety of objects with different states of their surfaces and in different measuring conditions (i.e. laboratory, workshop, outdoor).

Acknowledgments

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Czujnik do pomiaru przemieszczeń w płaszczyźnie wykorzystujący metodę integrującą interferometrię siatkową i plamkową

Streszczenie

W artykule przedstawiono nowe rozwiązanie głowicy do pomiaru przemieszczeń w płaszczyźnie z wykorzystaniem interferometrii siatkowej (GI) i cyfrowej interferometrii plamkowej (DSPI) jako uzupełniających się w jednym urządzeniu. Głównym celem proponowanego rozwiązania jest wskazanie nowych kierunków i możliwości rozwoju mikroczujników dla potrzeb mechaniki eksperymentalnej. W artykule przedstawiono projekt głowicy czujnika wraz z analizą tolerancji dla potrzeb wykonania prototypu. Dodatkowo wykonano analizy teoretyczne stanów polaryzacji we wnękowej konfiguracji czujnika oraz zaprezentowano polaryzacyjną zmianę fazy do automatycznej analizy obrazów prążkowych. Na koniec przedstawiono demonstrator technologii opracowanego czujnika i wskazano kierunki do dalszego rozwoju wraz z propozycją techniki replikacji.

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