Inspection and monitoring of engineering structures by means of optical displacement sensors based on interferometry techniques

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Abstract: Inspection and monitoring of engineering structures require simple, fast and remote acquisition, processing and visualization of relevant measuring data. Systems which utilize all above requirements are fundamental for Structural Health Monitoring (SHM). All necessary information should refer to safety threshold and sent to end user, who can accurately assess the health of an object in short time and schedule necessary actions in order to prevent accidences. The paper presents the novel approach to optical displacements sensors. Authors describe low-cost in-plane displacement and strain sensors for monitoring in crucial regions of big civil engineering structures (square millimeters area around welds, joints etc.) by means of two interferometry techniques: Grating Interferometry (GI) and Digital Speckle Pattern Interferometry (DSPI). In principle both of the methods applied have their specific requirements and can be used as complementary ones. GI requires specimen grating attached to the flat surface of an object under test, but it is the unique technique which may provide the information about fatigue process and increased residual stresses. DSPI works with a rough object surface, but due to differential measurements cannot be simply used for long time monitoring but to explore the actual behavior of a structure. We present both sensors working separately, but also we propose the technique which enables usage of the DSPI for long time or periodic monitoring by combining it in one sensor with GI in order to increase number of possible applications of the system. Both sensors can be manufactured by using low – cost replication technologies. The paper presents their mechanical and optical design along with laboratory tests of their main modules which are the sensor heads in the form of monolithic (plastic) and cavity waveguides. Finally, the exemplary applications of sensors in laboratory tests and on exemplary frame truss structure are presented and assessed.

Keywords: structural health monitoring, displacement sensor, grating interferometry, digital speckle pattern interferometry

1. Introduction

All types of engineering structures requires multiple types of monitoring on different levels and detailed inspection in order to prevent accidences [1]. Among many inspected/monitored parameters of such structures one of major value is measurement of displacement. There is a large variety of methods which are capable of such measurements (based on mechanical, electrical, optical and ultrasound techniques). Every method has its unique, dedicated properties in to surface requirements, measuring range, or sensitivity, which enables maintenance crews to create custom solutions dedicated for a certain type of measuring object. Most of these methods provide point-wise measurements often captured simultaneously in many distance points of an object. However here we focus on full-field measurement approach based on data captured by array detectors (CCD/CMOS). There are several methods which support this approach, including interferometric and noncoherent moire fringe techniques, digital image correlation, grid methods etc. Noncoherent, machine vision based methods are usually used for global, large field of view measurements and monitoring. If high sensitivity and more detailed inspections even in small crucial fields of a structure are required, interferometric methods are often applied as they provide information of possible failure much earlier than the standard global approach.

Therefore, the paper is focused on a novel concept of displacement sensors which use two interferometric techniques: Grating Interferometry (GI) [2] and Digital Speckle Pattern Interferometry (DSPI) [3] for in plane displacement measurements.

In the first part of the paper theoretical background on measurement techniques is presented. The second part of the paper is devoted to mechanical and optical design of the sensors along with their technical parameters.

Following section describes an application of the developed sensors and exemplary results of measurements of a truss structure. In the conclusion possible ways of further development are discussed.

2. Principles of the interferometric techniques applied in the sensors

2.1. Grating Interferometry

Grating Interferometry (GI) is used for determination of in-plane displacement of object under test. The element sensitive for displacement is diffraction grating applied onto an object surface. It 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, thou the diffracted beams propagate coaxially and perpendicularly to the object surface (fig. 1).

If any load is applied to the object, the grating suffers of deformation which corresponds to object changes. As the result the wavefronts of the incident beams are no longer plane and they carry information of in-plane displacement of the object. This information is coded in a fringe pattern gives as:

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

where: d – grating period, $u(x,y)$ – in-plane displacement perpendicular to object grating lines.

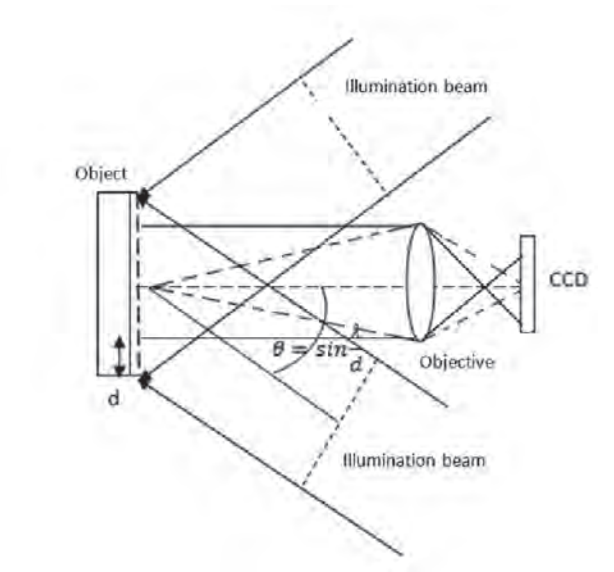

Fig. 1. Principles of grating inteferometry [2]

Rys. 1. Podstawy teoretyczne interferometrii siatkowej GI [2]

2.2. Digital Speckle Pattern Interferometry

Digital Speckle Pattern Interferometry [3] is widely used for displacement measurements of rough surfaces. In order to measure in-plane displacement with speckle pattern interferometry symmetrical illumination need to be provided in the configuration similar to GI method (fig. 2).

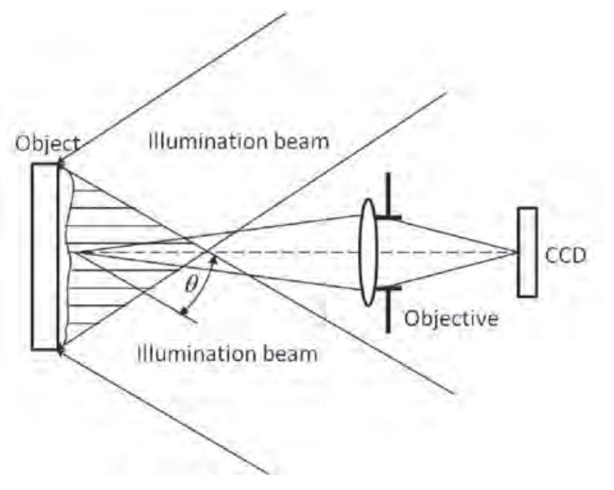

Fig. 2. Basic DSPI system for in-plane displacement measurement [3]

Rys. 2. Podstawowy system cyfrowej interferometrii plamkowej DSPI do pomiaru przemieszczeń w płaszczyźnie [3]

As distinct from other interferometric methods information is coded in a speckle pattern instead of a fringe pattern [3]. The speckle pattern from successive object states need to be correlated in order to obtain information about displacement value. The frame from reference state is subtracted from measuring state, fringes created by this operation are called correlation fringes and carry information about displacement of object:

$$I = I_1 - I_0 = 4\sqrt{I_O I_R}\sin(\psi_s + \frac{1}{2}\Delta\phi)\left|\sin\frac{1}{2}\Delta\phi\right|$$

where:

I_1, I_0 – intensities of subsequent speckle images,
I_O, I_R – intensities of illuminating beams,
ψ_s – random distribution of phase difference between illuminating beams (speckle background),

$\Delta\phi = [\frac{4\pi}{\lambda}u(x,y)]\sin\theta$ – change of phase caused by displacement (λ – wavelength, $u(x, y)$ – in-plane displacement, θ – angle of illuminating beams).

The main drawback of correlation fringes is high level of noise which need to be filtered before further processing.

2.3. Cons and pros for the methods

The described methods can be treated as complementary ones. Both have their advantages and drawbacks depending on measurement requirements and measuring objects. Main advantage of GI is that successive measurements have their reference at zero state of the object (the moment when object grating was applied), so one can get information about the cumulative displacement between measurements. Also the quality of displacement maps is higher due to lower noise in an interferogram. However GI requires carefull modification of an object surface through copying a high frequency diffraction grating. In the case of DSPI differential measurements are possible only (successive states of the object need to be correlated within system measurement range), so the system needs to remain on an object in order to grab series of images in short periods of time. The speckle pattern interferometry can be used in situation where it is impossible to apply high frequency grating onto an object.

3. Design of the proposed sensors

In the paper two sensors with slightly different properties are presented. The first one utilizes GI method only, while the second can implement both GI and DSPI.

The sensors should be compact and have modular design, so in case of maintenance the user can easily change major parts only and not the whole device. The modular design was provided by isolation of the functional blocks of the sensor which are:

- illumination module,
- detection module,
- sensor head (in two versions),
- data processing module.

The first three modules are integrated into one optomechatronics system, while the data processing module is stand alone device with dedicated software.

Mechanical design of both sensors is similar so they can meet some major requirements concerning compatibility with commercial optical elements, easy assemblies of main components and resistance to environmental conditions.

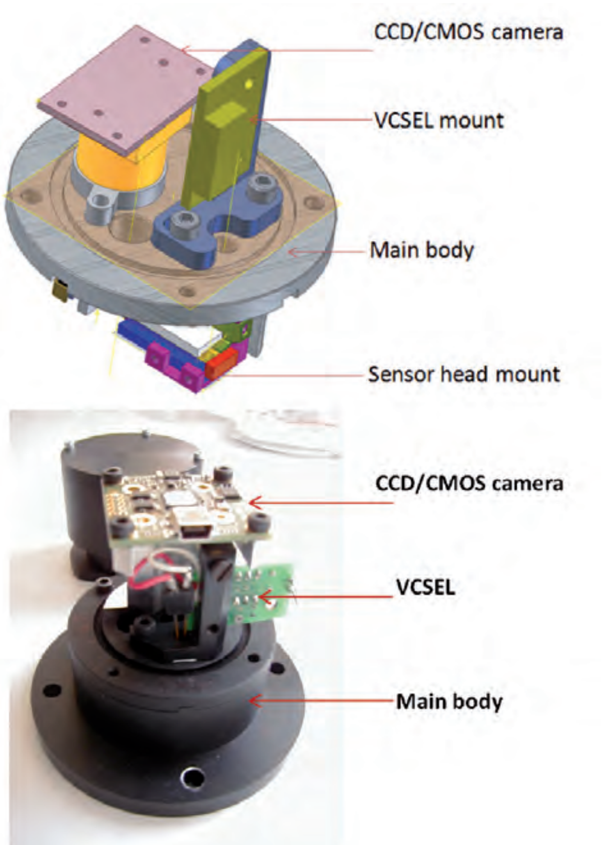

Fig. 3. Mechanical chassis [4] and photo of the final design
Rys. 3. Szkielet mechaniczny [4] i zdjęcie opracowanego rozwiązania

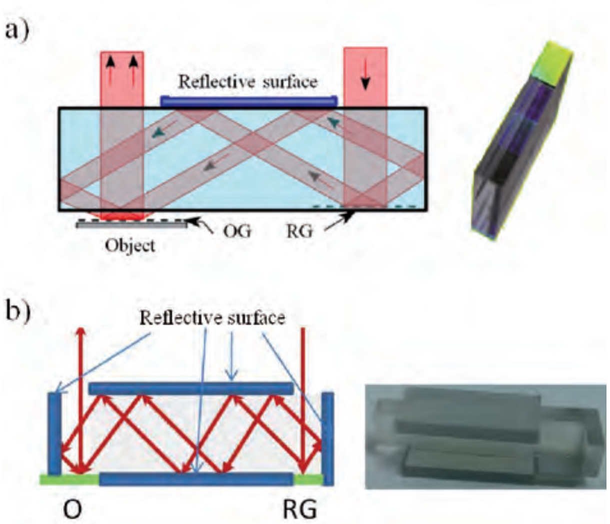

Fig. 4. Designed sensor heads: a) monolithic GI head b) air cavity GI/DSPI head, where RG – reference grating, OG – object grating, O – object
Rys. 4. Opracowane głowice pomiarowe a) monolityczna głowica GI b) wnękowa głowica GI/DSPI, gdzie RG – siatka referencyjna, OG – siatka obiektowa, O – obiekt

The chassis (fig. 3) consists of mountings for:

- Vertical Cavity Surface Emitting Laser (VCSEL) of 665 nm wavelength as light source;
- CCD or CMOS board level, c-mount based cameras;
- Collimating and imaging $\phi 6$ mm lens mounts;
- sensor head mount (for cavity based head or monolithic plastic head);
- casing mounts and wire holes.

Optical part of the design consists of the mentioned above VCSEL, collimating lens of 11 mm focal length and 9 mm working distance, which provides $\phi 2$ mm of illumination beam, complementary imaging lens with the same parameters, board level 1024 × 768 pixels CCD USB camera with 4,6 µm pixel and the sensor heads.

The first version of sensor head (fig. 4a) utilizes GI technique only and it is made as a monolithic plastic block (GI sensor) with a beam splitting grating [5], while the second one (fig. 4b) can utilize both GI and DSPI techniques. It is based on air cavity concept with free space beam propagation (GI/DSPI sensor) [4].

Tab. 1. The technical parameters of the sensors
Tab. 1. Parametry techniczne czujników

	GI sensor	GI/DSPI sensor
Head design	Monolithic from PMMA	Air cavity based
Influence of vibration	Minimized	Minimized but bigger than in GI sensor
Measuring field	2 mm × 2 mm	
Measuring range	up to 20 µm	
Resolution	~ 10 nm after AFPA[6],	
Sensitivity	417 nm/fringe	
Dimensions	ϕ60 mm × 115 mm	

The proposed sensors have their unique measuring capabilities. They can be used either for laboratory systems (GI/DSPI due to their bigger sensitivity for vibration and environmental conditions) or structural health monitoring systems (GI or GI/DSPI in the case when speckle mode is needed). Main technical parameters of the sensors are given in the tab. 1.

4. Application of GI and DSPI sensors

Before assembling sensors on the engineering structure some major test were performed in order to prove sensors correctness.

GI mode for both units was proved by the measurements of a reference 1200 lines/mm plane grating deposited on a glass plate. After processing of acquired fringe patterns for both sensors almost the same result was achieved and indicated a systematic error at the level of 240 nm. This proves that both heads have similar measuring capabilities in GI mode.

The correctness of DPSI mode in GI/DSPI sensor was tested on a sample of known geometry and mechanical properties which suffered from 3-point bending. The results were compared with FEM model and considered as also satisfactory.

As mentioned before the main application of proposed sensors is inspection and monitoring of engineering structures. Their functionality was tested through displacement measurements of a planar truss structure modeled and built by Integrated Laboratory of the Mechatronics System of Vehicles and Construction Machinery, Warsaw University of Technology.

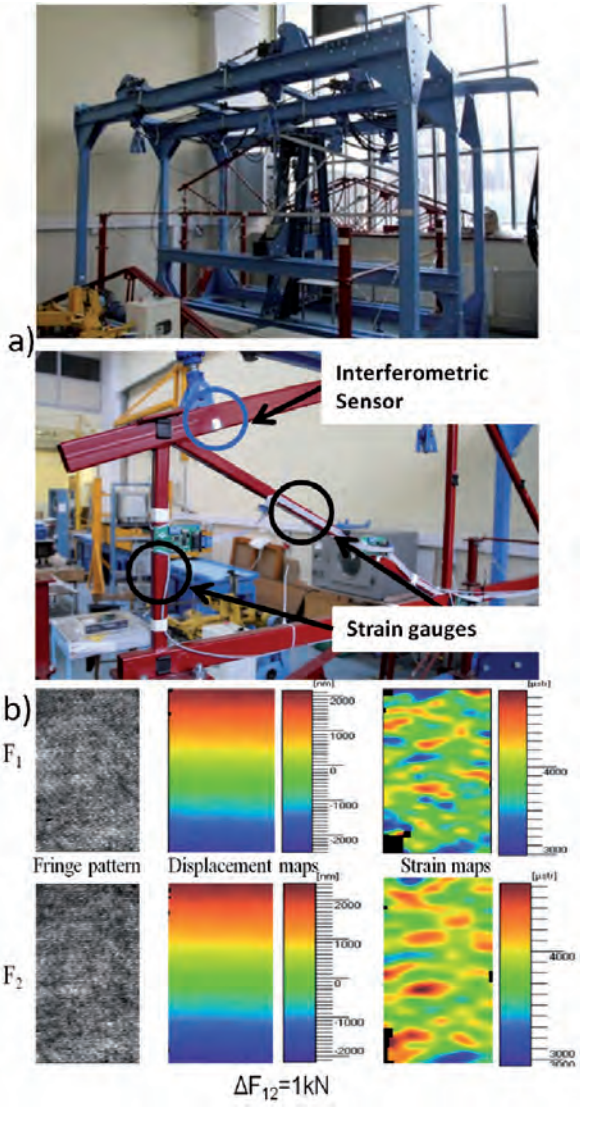

Fig. 5. Resultant test stand with mounting points of sensors (a) and achieved results for GI measurements (b)

Rys. 5. Stanowisko pomiarowe ze wskazanymi punktami montażu czujników (a) oraz wyniki otrzymane dla pomiaru interferometrią siatkową GI (b)

The test stand consisted of a steel frame with six hydraulic jacks attached to it. Such configuration allowed application of force to the investigated steel planar truss structure which was put inside.

The truss was built out of general purpose low-carbon steel St3 used typically in engineering construction.

The GI sensor was mounted on to the structure via dedicated mounts in some crucial points (fig. 5a). Due to high level of vibration, caused by hydraulics during tests, DSPI mode of GI/DSPI sensor was not performed. Applicability of DSPI will be prove after redesign of mount in order to provide vibration dumping.

GI data was gathered during load of the structure in two subsequent states with $\Delta F = 1$ kN. The resultant strain difference calculated from phase maps was 37 µS (fig. 5b). The achieved data corresponded with the results from strain gauges, which were mounted in the neighborhood of the sensors (fig. 5a).

5. Conclusion

The presented optical sensors based on GI and DSPI technique for inspection and monitoring of displacement in engineering structures open new possibilities for SHM purposes especially if detailed inspection in crucial areas of structure is required (fracture, fatigue phenomena).

The future work on the sensors will be focused on outdoor test on a variety of structures with different properties and long term monitoring requirements. Also some design work need to be performed especially in GI/DSPI sensor in order to allow measurements in harsher conditions.

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Zastosowanie optycznych czujników przemieszczeń, wykorzystujących techniki interferometryczne, do kontroli i monitoringu konstrukcji inżynierskich

Streszczenie: Kontrola i monitoring konstrukcji inżynierskich wymaga prostej, szybkiej i zdalnej akwizycji oraz przetwarzania i wizualizacji danych pomiarowych. Systemy spełniające powyższe wymagania są niezbędne do monitorowania stanu technicznego konstrukcji (ang. *Structural Health Monitoring* – SHM). Dane uzyskiwane przez systemy monitoringu powinny odnosić się do założonych poziomów bezpieczeństwa i być wysłane do końcowego użytkownika, aby mógł on w krótkim czasie ocenić stan obiektu i zaplanować niezbędne działania celem zapobiegnięcia wypadkom. W artykule zaprezentowano nowe podejście do optycznych czujników przemieszczeń. Opisano niskokosztową głowicę interferometryczną wykorzystującą metodę interferometrii siatkowej i cyfrowej interferometrii plamkowej do pomiarów przemieszczenia i odkształcenia w płaszczyźnie. Przedstawiono jej zastosowanie w monitoringu newralgicznych punktów wielkogabarytowych konstrukcji inżynierskich (regiony wokół spawów, połączeń itp.). W pracy przedstawiono również projekt mechaniczny i optyczny czujników oraz testy laboratoryjne ich głównych modułów (falowodowych głowic pomiarowych). Na koniec przedstawiono aplikację opracowanych czujników na przykładowej konstrukcji kratownicowej.

Słowa kluczowe: monitorowanie stanu technicznego konstrukcji, czujnik przemieszczeń, interferometria siatkowa, cyfrowa interferometria plamkowa

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