THE MEASUREMENT OF THERMALLY INDUCED IN-PLANE DISPLACEMENTS USING FIBRE-OPTIC GRATING INTERFEROMETRY

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The miniaturised, sensor type, full-field fibre optic grating interferometer for simultaneous u and v in-plane displacements measurements is presented. The usefulness of the sensor for thermally induced displacements and strains measurements is proved. The paper contains the sensor arrangement description as well as experimental results.

1. Introduction

Due to the development in electronic technology the newly created devices are characterised by the high level of miniaturisation and integration of inner components. In these devices the problem of high power densities and increased heat emission has very often to be encountered. The reduction of heat emission and cooling of the systems became an important issue in electronic packaging design. On the other hand the thermal load induces strains due to the differences in thermal expansion coefficients in various components of electronic element which can lead to its damage [1]. Therefore at the stage of design of electronic devices the influence of thermal load on the behaviour of individual elements has to be analysed.

The goal of this work is to present the tool for full-field determination of thermally induced displacements and strains in electronic elements. The proposed method is a grating interferometry with conjugated wavefronts (called also moiré interferometry) [2,3]. Basing on this method, the miniaturised, two-directional fibre optic grating interferometer (FO-GI) has been build. The arrangement of the sensor in one and two directional version as well as experimental results are presented.

2. Principle of sensor operation and design

Grating interferometry requires replication of a high density (*e.g.* 1200 l/mm) diffraction grating DG on the object under test. This grating is illuminated by two mutually coherent beams A1 and A2 with plane wavefronts. The angles of incidence of the beams are tuned to the plus and minus first diffraction order angles of the grating. After being diffracted on the grating the beams propagate co-axially along the direction normal to the grating and interfere. When the specimen is thermally loaded, its surface is deformed and simultaneously grating lines are distorted. In the observation plane the amplitudes of emerging beams can be described as:

$$E_{+1}^{A1} = \exp\left[i\left(\frac{2\pi}{p}u(x,y) + \frac{2\pi}{\lambda}w(x,y)\right)\right], \tag{1}$$

$$E_{-1}^{A2} = \exp\left[-i\left(\frac{2\pi}{p}u(x,y) - \frac{2\pi}{\lambda}w(x,y)\right)\right], \tag{2}$$

where p is the spatial period of the grating, u(x,y)is the in-plane displacement function in x direction corresponding to the departure of the grating lines from straightness, w(x,y) is the out-of-plane displacement function in z direction, λ - the wavelength.

The intensity distribution in the interference pattern is:

$$I(x,y) = 2\left[1 + \cos\left(\frac{4\pi}{p}u(x,y)\right)\right]. \tag{3}$$

The resulting interference fringes obtained at the output of the system carry the information about in-plane displacements u(x,y) of the object under test (the sensitivity: 0.416 µm per fringe order). By using a crossed-line diffraction grating and illuminating it in the perpendicular direction, the information about in-plane displacment v(x,y) can be also obtained (the equatins describing the amplitudes of the beams and the intensity distribution in the interference pattern are analogous to equatins 1-2 and 3).

There are several opto-mechanical systems which enable to apply the a.m. principle of measurement, however due to the usage of bulk optics they are often not very convenient for versatile, quasi-industrial measurements [4]. The sensor presented in this work comprises of a fibre optic version of grating interferometer [5]. The basic arrangement of this interferometer is shown in Fig. 1. The light from a single mode laser diode LD (the Hitachi HL7851G) is launched via Faraday isolator and microscope objective (x40) into the single-mode optical fibre OF. Next the light is split into two interferometer arms using a directional coupler DC (splitting ratio: 50/50). The output beams are collimated using the collimating optics CO (the focal length of the lenses is 56 mm). The

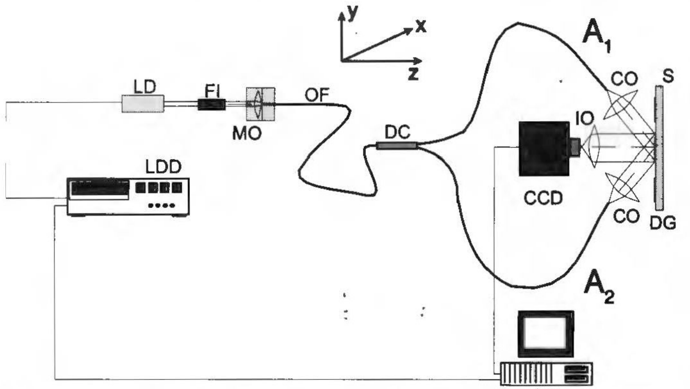

Fig. 1. Basic arrangement of a fibre optic grating interferometer. LD-laser diode, FI-Faraday isolator, MO - microscope lens, OF-optical fibre, DC-directional coupler, CO-collimating optics, S-specimen, DG - diffraction grating, IO-imaging optics.

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interferograms are detected by a CCD camera and analysed automatically using a PC computer.

In some cases, when the information about one of displacement components (*e.g.* u displacement) is sufficient, the presented above one-directional FO-GI configuration can be recommended. However in most engineering applications the description of displacement fields in two orthogonal directions (in order to obtain the u and v displacements) is necessary. Therefore the extension of the FO-GI performance to the 2-directional version is proposed. The concept of this extension is based on the wavelength multiplexing where the information about each of displacement fields is coded using the laser diode light of the different wavelength [6]. The schematic drawing of the two-directional sensor is shown in Fig. 2.

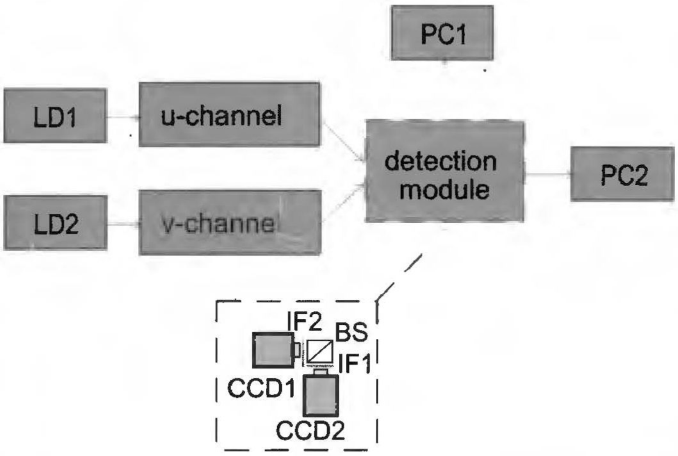

Fig. 2. Principle of operation of two-channel grating interferometer. LD1, LD2- laser diodes, BS- beam splitter IF1, IF2 - interference filters, PC1, PC2-personal computers. The scheme for u and v channel is shown in Fig. 1.

In each channel a FO-GI shown in Fig. 1 is implemented. As a light sources the Hitachi HL7851G emitting at 780 nm (LD1, x direction) and the Sharp LTO30MD emitting at 754 nm (LD2, y direction) laser diodes are used. The separation of u and v displacement maps was performed using a beam splitter and two interference filters with the centre wavelengths values 780 nm and 754 nm respectively. The spectral width at the half maximum at the transmitance curve of the filters was 10 nm. The cross talk between the u and v interferograms is at the level of 1%. The interferograms detected by two CCD cameras and captured by two frame-grabbers controlled by PC computers.

The in-plane displacement measurement accuracy of the 2-directional FO-GI was evaluated for 1/7 of interference fringe [6].

3. Application example

The FO-GI has been applied for the measurement of the thermally induced displacements and strains in the electronic element UCY74S405N. This element consists of an electronic chip connected with external legs by metal wires placed in epoxy resin encapsulation. (Fig. 3a). During the experiment the behaviour of UCY74S405N element in normal operating conditions (applied voltage: 5 V) was tested. The temperature distribution at the surface of the element was monitored using AGEMA 470 thermovision camera (Fig. 3b). The maximum temperature was found in the proximity of electronic chip placement. In order to work with FO-GI on the surface of the element (6 mm x 9 mm) a diffraction grating of the density 1200 lines per mm was copied.

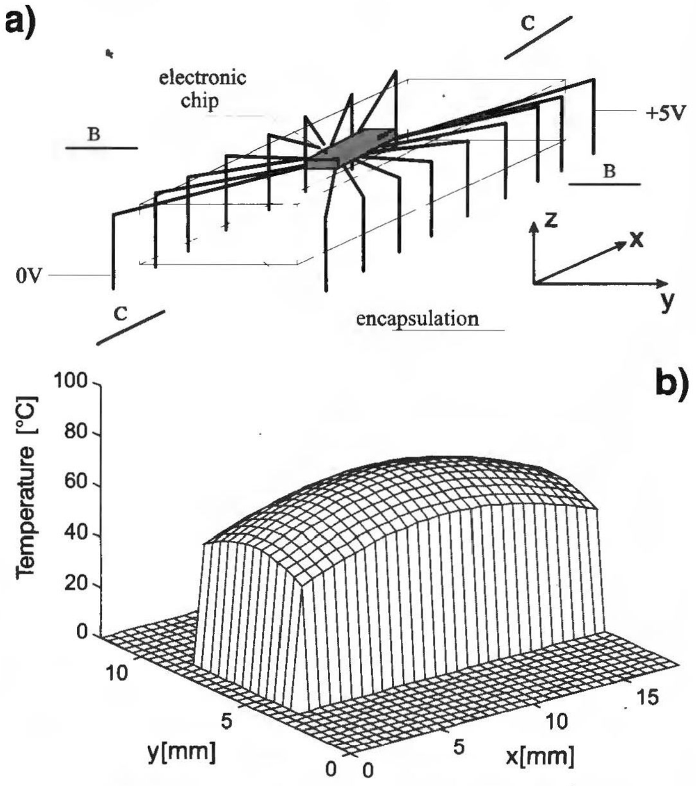

Fig. 3 The schematic drawing of a UCY74S405N element (a) and the temperature distribution on the heated element surface. B-B, C-C - the cross sections applied in Fig. 5 and 6.

During the experimental procedure, the interferograms were analysed using the spatial-carrier phase stepping method (SCPS) [7]. The main advantage of the method is its ability to analyse the results on the base of single fringe pattern which allows for the measurement of the dynamic events, like thermally induced displacements.

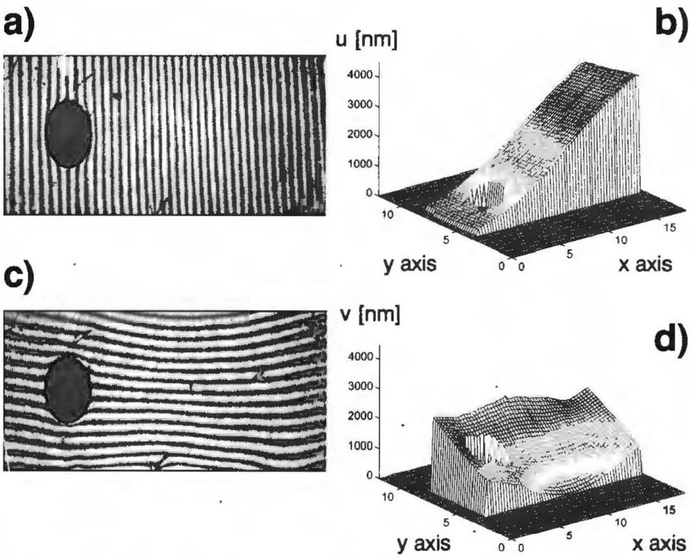

Fig. 4. The interferograms obtained for a) x and c) y directions and 3-D plots of b) u and d) v in-plane displacement of the heated UCY74S405N element. In the black area the surface of the element was distorted and the diffraction grating was not replicated.

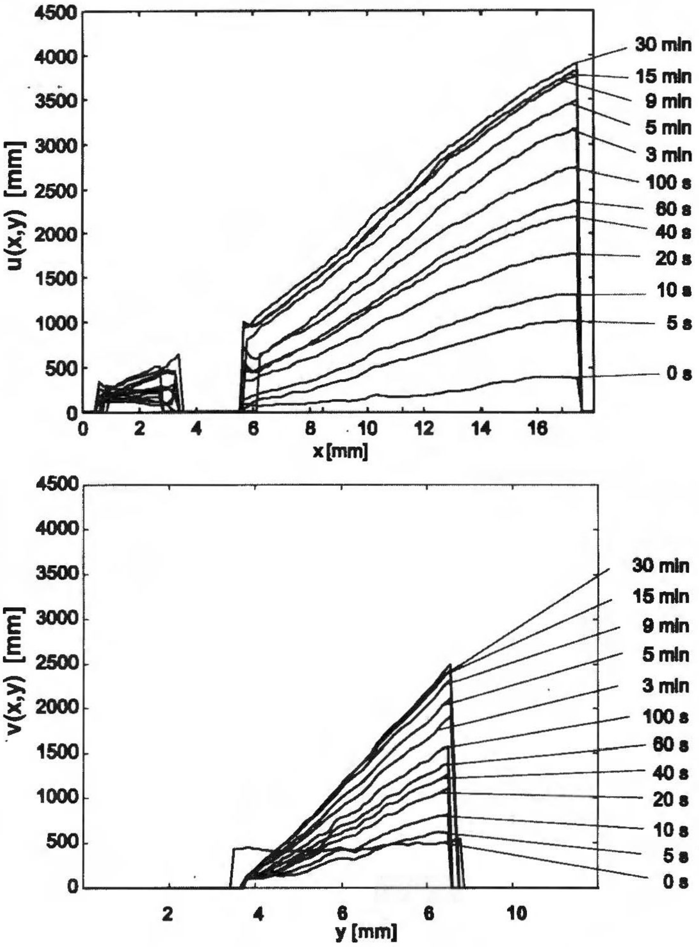

Fig. 5. The profilograms of a) u (cross section C-C) and b) v (cross section B-B) displacements obtained during monitoring of the thermally loaded UCY74S405N element.

The exemplary interferograms representing u and v displacement fields of the heated electronic element and the recovered in-plane displacement 3-D maps are shown in Fig. 4.

During the tests of the system the u and v fields of UCY 74S405N element were monitored and registered simultaneously in the chosen time intervals (5 s, 10 s, 20 s. etc. after switching on the element). To show the monitoring capability the sequential plots of u and v displacements taken at the cross sections C-C and B-B (see Fig. 3a) respectively are presented in Fig. 5.

As a result of the differentiation of the relevant displacement fields the strain distributions ε_x and ε_y were obtained. The strain profiles are shown in Fig. 6a (ε_x) and 6b (ε_y). The accumulation of the strains occur close to the chip region. The strains are at the level of 0.045% for ε_x and 0.06% for ε_y.

4. Conclusions

The presented two-directional FO-GI is proved to be a useful tool for the electronic elements testing. The possible applications of the system cover not only the testing of the thermally loaded electronic elements, but also the measurement of displacement fields and strains on various electronic materials, components and packages. The laser diode and fibre-optic based configuration will allow in future to build a compact, versatile sensor for numerous tasks in electronic, material engineering and mechanics industries.

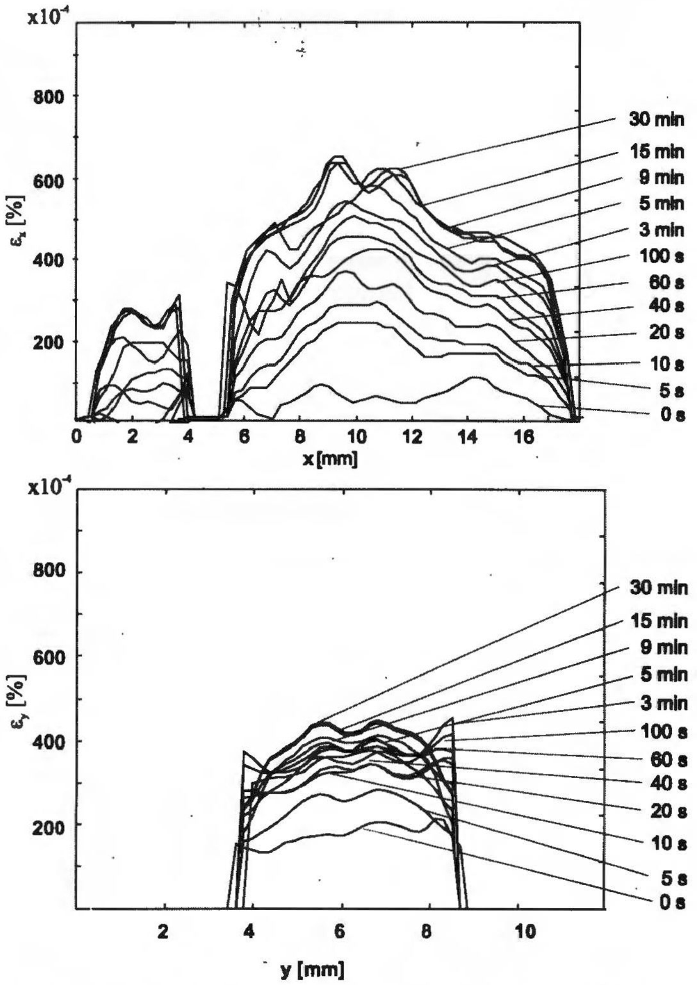

Fig. 6. The profilograms of a) ε_x (cross section C-C) and b) ε_y (cross section B-B) strains obtained during monitoring of the thermally loaded UCY74S405N element.

Short biography note

Anna KOZŁOWSKA received her MSc degree in 1992 from the Faculty of Mechatronics (former Precision Mechanics) at Warsaw University of Technology. Since 1992 she pursued the doctoral studies in Institute of Micromechanics and Photonics at Mechatronics Department. In 1997 she joined the Institute of Electronic Materials Technology. Her main interests are in the field of fibre-optics and laser diodes based systems and their applications in optoelectronics and experimental mechanics.

Małgorzata KUJAWIŃSKA, professor of applied optics, SPIE Fellow, received her MSc, PhD and PhDhab at Warsaw University of Technology. Her main scientific interests include full-field optical methods of testing, image processing, machine vision and their application in mechatronics, material engineering, experimental mechanics and industrial control.

This work was performed in Institute of Micromechanics and Photonics, Warsaw University of Technology within Anna Kozłowska's PhD thesis.

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COMPUTERISED TWO-STATE THERMOANEMOMETER

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Computerised thermoanemometric system presented hereby can be used for measurements of velocity and temperature fields in non-isothermal flows. This paper presents the theoretical bases and circuit designs.

1. Introduction

Studies of velocity and temperature fields in gas flows are fundamental in numerous scientific and research applications in modern metrology. While employed in aviation and car industry, ventilation and air-conditioning, cooling and heating systems, they prove to be absolutely crucial. In most of their applications in the field of technology and research, the studies of velocity and temperature distribution in the flowing gas make an additional issue; still they will be very important in consideration of the whole process. In both cases correct results, which determine the success of the whole enterprise, can be obtained only when the appropriate measuring instruments are used.

One version of the thermoanemometric method is a specialised technique for measurement of non-isothermal parameters of the gas flow using a single measuring probe with a hot wire [1-3]. Following the traditional thermoanemometric method, the measurements of non-isothermal flows were possible only when the probe was supplied with an additional, temperature compensating element. Since the measuring and compensating element were fitted at some distance from one another, serious measurement errors were involved in measurements of flows accompanied by effects of temperature gradient. The new method consists in defining the velocity and temperature of the medium using an output signal from a constant temperature anemometer where the overheating ratio of the single measuring wire is time -variant and changes periodically. This is called a two-state thermoanemometer. The main advantage of the new approach is that temperature-compensated flow velocity measurements and temperature measurements are realised within the same space, determined by the dimensions of the thermoanemometric wire.

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Basing on this method, a computerised thermoanemometric system was designed. It consists of a hot-wire sensor, a computer card, a PC computer and the specialised software that does measuring algorithms. This paper presents the measuring method as well as the design and functioning of the measuring circuit.

2. A two-state thermoanemometer

It is possible to determine the velocity and temperature in non-isothermal flows using a constant-temperature thermoanemometer where the overheating ratio of the single thermoanemometric wire is time-variant and changes in cycles. Thus controlled constant temperature system operates in such a way that wire temperature varies periodically between two values, indicated with the symbols 1 and 2. Following each change, the current flowing through the sensor can be duly measured once the steady state is reached. Let us assume that the static, mathematical model of a thermoanemometric sensor which can be used to describe heat transfer between the sensor wire and the flowing medium is as follows [4]:

$$I^2R = (A + B\sqrt{V})(R - R_g) \qquad (1)$$

where: I - electrical current flowing through the wire; R - resistance of the hot wire; R_g -resistance of the wire at the temperature of the medium T_g; V- flow velocity of the medium; A,B - parameters in the model.

The relation between the resistance of the wire and its temperature is taken to be linear:

$$R = R_0(1 + \alpha_0(T - T_0)) \qquad (2)$$

where: R - wire resistance at the temperature T; R_0 - wire resistance at the reference temperature T_0; α_0 - a temperature coefficient of wire resistance at the temperature T_0.

Let us assume that the parameters A and B remain constant over the whole analysed range of wire and medium temperature variations. Once we assume that velocity and temperature of the medium do not change in between the changes of the overheating ratio, then in accordance with (1) it will be possible to describe the sensor in its both steady states with the following system of equations:

$$I_i^2R_i = (A + B\sqrt{V})(R_i - R_g), \; ....i=1,2. \qquad (3)$$

From the system of equations (3) we can determine the velocity:

$$v = \left[\left(\frac{I_2^2R_2 - I_1^2R_1}{R_2 - R_1} - A\right)\frac{1}{B}\right]^2 \qquad (4)$$

and the resistance of the wire at the temperature of the medium: