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Opto-Electronics Review 25 (2017) 19–23

Contents lists available at ScienceDirect

Opto-Electronics Review

journal homepage: http://www.journals.elsevier.com/opto-electronics review

Deformation sensing with a multimode POF using speckle correlation processing method

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ARTICLE INFO

Article history:
Available online 2 March 2017

Keywords:
Plastic optical fibre
Speckle pattern
Average speckle size
Correlation processing

ABSTRACT

A deformation sensing technique with a multimode plastic optical fibre based on intensity speckle patterns' correlation coefficient measurement has been presented. Influence of the average speckle size on results of deformation measuring has been studied and discussed. The presented sensing technique provides a good linear response to the applied deformation in a relatively wide operation region. It is shown that the proposed technique is highly sensitive, low-cost and simple to implement in practice.

1. Introduction

In recent years sensing with optical fibres has grown to become a suitable technique for a variety of the engineering applications. General advantages of optical fibre sensors over traditional measurement techniques are their light weight, small size, and immunity to electromagnetic interferences [1–3]. Fibre optic sensors have found wide usage in deformation measuring and structural health monitoring as they can be embedded into materials for monitoring the mechanical properties of structures. Currently, the intensity detection fibre sensors [4–7] and the interferometric fibre sensors [8–12] have been suggested for this purpose. Intensity-based sensors use changes in the intensity of the transmitted light due to an induced perturbation. This type of a sensor is stable to environmental influences but it has low sensitivity that limits its application. Interferometric fibre sensors convert the fibre external perturbations into changes of the phase of the light transmission over the fibre. Thus, interferometric fibre measuring systems can be used to detect deformations with high sensitivity. Schemes of conventional fibre interferometers require two interacting waves with identical polarization states which are easily achievable when a sensitive arm of an interferometer is a single-mode fibre. However, a single-mode fibre is very brittle, so it may not be easy to implement or even pretty difficult in some engineering applications. Therefore, in some practical cases using a multimode optical fibre (MMF) is much more convenient than using a single-mode fibre [13].

As it is well-known, when coherent light propagates through an MMF, the speckle pattern is formed at the fibre output as a result of the intermodal interference. Even the small perturbations of the MMF cause the change of propagation conditions of guided modes and, consequently, the change of spatial distributions of a speckle pattern. An analysis of the changes in the speckle pattern at the output end of a multimode fibre can be used to obtain information about the perturbation of the fibre which is utilized for a sensor design [14–16]. Based on this phenomenon, various schemes of sensors for the control of different types of deformation were reported. Yu *et al.* [17,18] developed a multimode fibre sensing technique for detection of sub-micrometer displacements using speckle intensity variations caused by the periodic deformation mechanism. They have shown that the sensitivity of this method can be as high as for a dual-arm interferometric fibre sensor. The displacement sensor proposed by Garcia and Tabib-Azar [19] had the potential to detect the force and displacement according to the fibre mechanical perturbation with high resolution, but the system concept was too difficult for practical realization. Afterwards, the system to estimate the applied stress sensed from a set of multimode fibres which were attached to the surface of a smart structure was reported [20]. Zhang and Ansari [21] developed a fibre-optic speckle-intensity sensor and demonstrated its use as embedded sensors in concrete for the detection and measurement of crack opening displacements. The achieved results show a good linearity, but this scheme is limited in a dynamic range because it is based on a weak perturbation approximation. Another sensing

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http://dx.doi.org/10.1016/j.opelre.2017.02.002

mechanism for measuring low strain based on an analysis of the speckle pattern at the output of a multimode optical fibre embedded in the steel plate was reported in Ref. [22]. The change in the speckle pattern was detected by an array of photodetectors and correlated with the strain using a neural-network technique. The method was shown to be capable of measuring strains in the range from 0 to 25 microstrains with a resolution around 0.1 microstrain.

The great interest presents using a plastic optical fibre (POF) for deformation measurements, since it has additional advantages in comparison with a silica fibre, including high elastic strain limits, high fracture toughness, excellent flexibility and high sensitivity to deformation [1,23]. In addition, POF can be easily surface mounted or embedded in engineering structures and composite materials to assess their reliability. Most of the reported applications using multimode POF speckle-based sensors are not suitable for the interferometric deformation measurement due to the complexity of interpretation of the interference speckle signal at the fibre output or the oversensitivity of the sensor principle. Nevertheless, in Ref. [24] the applicability of a commercial POF in electronic speckle pattern interferometry (ESPI) has been demonstrated. The obtained results show advantages of a POF in comparison with a glass fibre used in an ESPI configuration. In Refs. [25,26] some photorefractive materials are used to stabilize the processed speckle pattern. This allows reducing the extra noise caused by the oversensitivity of the fibre speckle pattern. However, these systems were too complicated to be implemented in practice and are not suitable for low cost applications. This problem has been solved in Ref. [27] analyzing the geometrical properties of the speckle pattern to determine the fine strain measurements using a POF.

One promising direction in this area is the use of the correlation methods of signal processing which allow a constructed simple fibre optic sensor using only laser source, multimode fibre and digital camera. The speckle pattern changes can be detected by comparing the resulting speckle pattern with a reference pattern. A good comparison of the speckle patterns can be accomplished by measuring the correlation coefficient for these signals [28].

In this paper, the interferometric sensing technique based on the change of spatial distributions of the speckle pattern formed at the end of a multimode POF is demonstrated. In addition, the analysis of the influence of an average speckle size in a deformation sensing with a multimode POF using the speckle correlation processing is carried out.

2. Sensing principle

As it was mentioned above, when the multimode optical fibre transmitting the coherent light is perturbed, distribution of the speckle intensities changes with the perturbation which can be used in metrological applications. Of interest in the speckle metrology is a number of speckles and an average speckle size. The average size of the speckle of the light field formed by a multimode fibre in the plane placed at the distance d from its output can be calculated as [16]

$$S_d = 1.22d\left(\frac{\lambda}{R}\right), \tag{1}$$

where λ is the wavelength of the light source and R is the diameter of a fibre core. This equation demonstrates the relationship between the speckle size and the distance from the fibre to the observation plane.

In this section we show that the deformation sensing can be achieved by utilizing correlation processing of the intensity speckle fields in a multimode POF. In other words, by taking the speckle patterns before and after the perturbation of the fibre, the perturbation value can be obtained from an intensity correlation coefficient of these speckle fields.

2.1. Correlation processing method

When the multimode sensing fibre is subjected to a perturbation, the optical path length of propagating modes undergoes changes. These changes can be detected by comparing the resulting output speckle pattern with a reference pattern. If I_1 is the output pattern when there is no external effect to the fibre and I_2 is the corresponding output pattern when there is a perturbation, the intensity correlation coefficient between the two speckle images can be expressed as

$$C = \frac{\langle I_1 I_2\rangle - \langle I_1\rangle\langle I_2\rangle}{\sqrt{\left(\langle I_1^2\rangle - \langle I_1\rangle^2\right)^2\left(\langle I_2^2\rangle - \langle I_2\rangle^2\right)^2}}, \tag{2}$$

where the angle brackets represent the average intensity of the pixels under consideration. The correlation coefficient takes the value one if the intensity distribution of the speckle pattern I_2 correlated with I_1 is identical to it and decreases gradually with the speckle pattern's change.

The intensity correlation coefficient between two speckle patterns at the output of a multimode fibre before and after deformation, respectively, is associated with a maximal additional phase difference between guided modes as follows [29]

$$C = \frac{\sin^2\left(\Delta\varphi_{max}/2\right)}{\left(\Delta\varphi_{max}/2\right)^2}. \tag{3}$$

We assume that the variation of Δj_{max} is uniformly distributed in the interval from 0 to some maximum value. According to this, the maximum additional phase difference due to a change of fibre length Δl can be estimated

$$\Delta\varphi_{max} = \frac{2\pi}{\lambda}\varepsilon n\Delta l\left(\frac{1}{\cos(\theta_m)} - \frac{1}{\cos(\theta_0)}\right), \tag{4}$$

where λ is the wavelength of the light source, ε represents the strain optics factor, n is the refractive index of the fibre core, θ_m and θ_0 is the incident angle of the m-th and 0-th modal wave fields with respect to the fibre axis. In the case of excitation in the fibre a large number of modes (e.g., several hundred modes), θ_m can be approximately calculated from the critical angle of the total internal reflection.

Combining Eqs. (3) and (4) the expression for the correlation coefficient can be written as

$$C = \frac{\sin^2\left[\frac{\pi\varepsilon n\Delta l}{\lambda}\left(\frac{1}{\cos(\theta_m)} - 1\right)\right]}{\left[\frac{\pi\varepsilon n\Delta l}{\lambda}\left(\frac{1}{\cos(\theta_m)} - 1\right)\right]^2}. \tag{5}$$

This equation shows a direct relationship between the elongation of the fibre Δl and the correlation coefficient of speckle patterns. Thus, according to Eq. (5), the fibre elongation can be obtained from the measured value of a correlation coefficient.

2.2. Experimental setup

The schematic of the experimental setup is depicted in Fig. 1. The light from an He-Ne laser with the wavelength λ = 0.6328 μm is directly coupled (without using launching optic) to the 1 m section of a standard PMMA step-index fibre with a 980/1000 μm core/cladding and numerical aperture of 0.5. The studied fibre was mounted on special holders at it ends, what provided its fixing and tension. The axial deformation of the sensitive part of a fibre with length of about 0.9 m was produced by a micrometer translation stage along the fibre axis. For this purpose, the second holder was attached to the translation stage. Intensity distribution of the speckle pattern remains stable over the time, when external conditions maintain unchanged. The small displacement of the

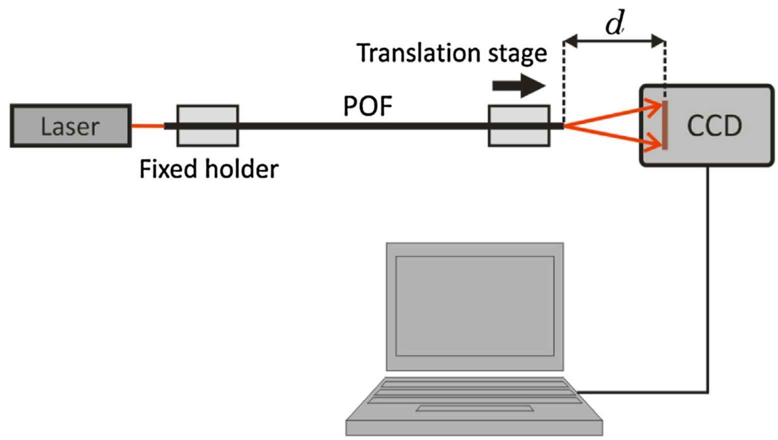

Fig. 1. Scheme of the experimental setup.

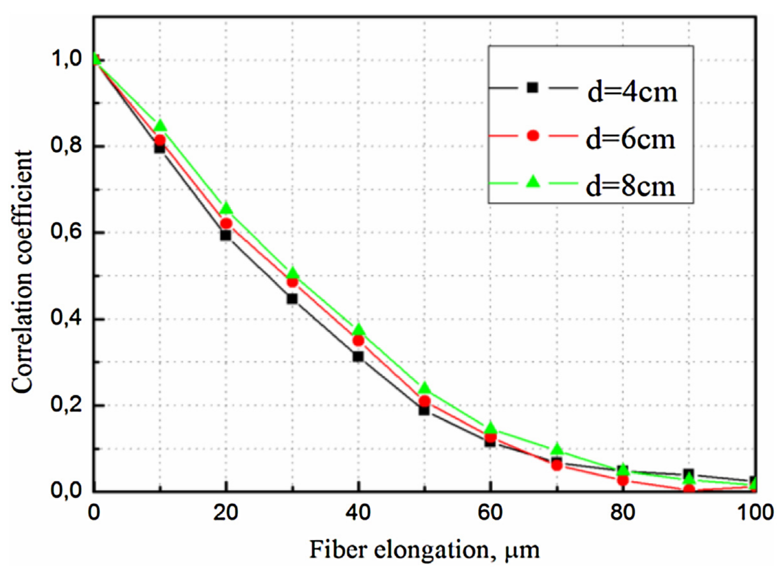

Fig. 2. Dependence of the correlation coefficient of speckle patterns on elongation of a multimode POF obtained for different distances from a fibre to a CCD sensor.

translation stage would cause a small elongation of the sensing fibre. Thus, by capturing the fibre speckle intensity distributions with a CCD camera, the intensity speckle pattern evaluation can be performed by a computer. The first digital camera records a reference image of the speckle pattern which corresponds to the initial state of a fibre waveguide. Deformation of the fibre due to external influence causes changes in the spatial position of the speckles. The correlation coefficient between speckle patterns before and after the deformation is calculated by using the developed software. According to the calculated value of the correlation coefficient the elongation of fibre is obtained. It should be noted that when a tension load is applied and then removed, the original speckle pattern is recovered what confirms that the measurement is reproducible. The effect of a stress relaxation has a small effect on the change of a correlation coefficient between speckle patterns in the strain measurement.

To provide the optimal condition of the CCD camera illumination, one must ensure the observance of the Nyquist criterion [30] by which the average speckle size in the registration plane should be much larger than the pixel size of the digital camera. This is necessary for that individual speckles to be well separated in the registered image.

3. Results and discussion

In order to evaluate the sensing system response to a fibre axial deformation initially the system was used for the measurement dependence of the intensity correlation coefficient of speckle patterns on the fibre elongation. The curves shown in Fig. 2 correspond to intensity speckle patterns recorded for fibre elongations ranging from 0 to 100 μm, in 10 μm steps. First, the distance *d* between the fibre end and the CCD sensor was fixed to 4 cm. Each point represents the result obtained after applying the algorithm described in Sect. 2 to the initial speckle pattern correlated with that associated to the corresponding displacement of the translation stage. Further, the distance *d* was changed to 6 cm and 8 cm, respectively in order to increase the speckle size to half of its previous value. As it can be seen from Fig. 2, all the curves are in very similar shapes. The better sensitivity (higher slope of the linear region of curve) is obtained for the shorter distance which corresponds to the smaller average speckle size.

We can see from the curves presented in Fig. 2 that an intensity correlation coefficient approximately linearly changes with the fibre elongation in the range from 0 to 50 μm and it fluctuates slowly as the fibre elongation is higher than this value. This is

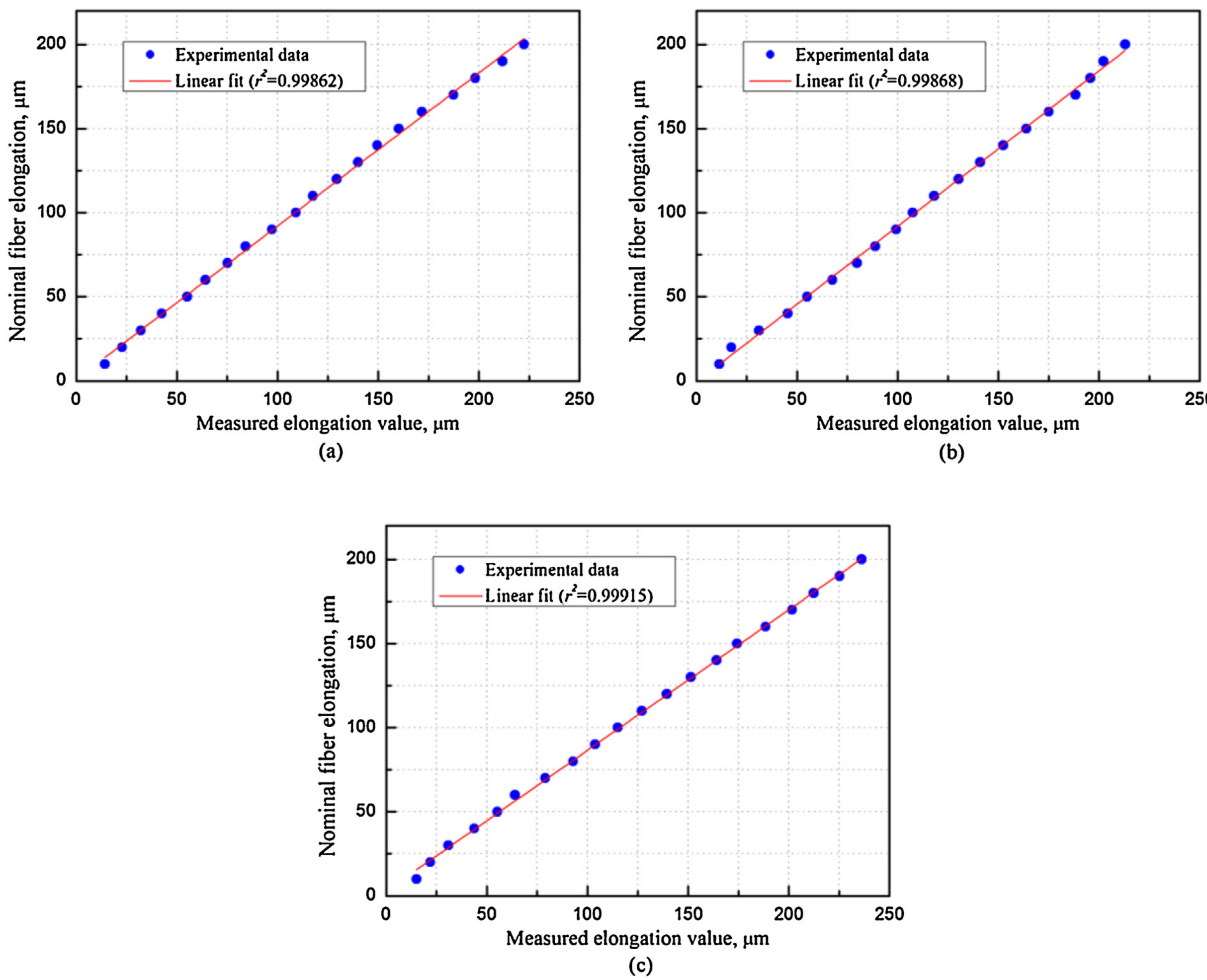

Fig. 3. A measured fibre elongation *vs.* the real applied deformation for $d = 4$ cm (a), $d = 6$ cm (b), and $d = 8$ cm (c). The circles represent the experimental data and the solid line represents the linear fitted curve.

primarily due to the maximal additional phase difference between guided modes being larger than 2π. To increase the measurement range, the reference speckle pattern can be rewriting. In this case, a fibre elongation value obtained after the previous rewrite procedure is added to the value obtained before rewriting.

In order to study the effect of the speckle size on the deformation measuring with a multimode POF, we present the results comparing the measured fibre elongation and reference (nominal) displacement of the translation stage (see Fig. 3). The fibre underwent a total deformation of 200 μm with the fibre elongation steps of 10 μm. These measurements were carried out for different distances between an the fibre exit face and the CCD camera. The measured fibre elongations were then obtained from the experimental transference curves shown in Fig. 2 by the second order polynomial fits.

The obtained results show that there is generally a good agreement between the measured fibre elongation and the applied deformation. It demonstrates that the sensing scheme is able to present an almost true linear response to the applied deformation, with the results compatible to nominal deformation values. The linear regression analysis presents correlation coefficient values (r^2) greater than 0.99 for all three cases. However, the total measured fibre elongation becomes slightly larger than the nominal axial deformation with the speckle size increasing. The maximum average absolute error was obtained for the largest value of speckle size and is of 2.35 μm which demonstrates that the presented sensing technique is suitable for many structural applications.

Some factors can influence the measurement accuracy, but the main ones are of a statistical nature of the measured correlation parameter and environmental factors. Influence of the previous can be significantly reduced by using a single-mode fibre to couple the light from laser source into the sensing fibre, as proposed in Ref. [31], providing an unchanged incident angle.

4. Conclusions

In this paper the application of a multimode POF to the deformation sensing using a speckle pattern correlation has been demonstrated. The response of a sensing system to the applied axial deformation was studied for different average speckle sizes. The obtained results show a good linear sensor response over a wide operation range, but the total fibre elongations exceed the applied axial deformation due to the measurement error. With the increasing of the average speckle size the amount of measurement error grows. The updated reference speckle pattern can be used to extend the measurement range of this method. In this case, the previous speckle pattern before the current update image is used as a reference pattern. This approach allows using this technique for measuring in a wider deformation range.

The proposed method requires a previous calibration procedure. The parameters, such as setup geometry, CCD array resolution, temperature, etc., become relevant for deriving the transference curve from which fibre elongations are obtained through the measured correlation coefficient values.

The presented sensing technique is low-cost and simple to implement in practice, providing a high sensitivity to the applied deformation with relatively low measurement errors. This technique can potentially be used in applications where the compact sensor size and low-cost are needed. He-Ne laser can be replaced in the scheme by a semiconductor one, if it is a single mode and sufficiently stable coherence light source. It could allow for an extra simplification of the sensor scheme. Sensor's potential applications are limited to the measurement of small deformations and best suited for a laboratory testing environment. Applications in civil structures require sensors with a larger dynamic range. In addition, the sensor's length is limited by the length in which contrast of a speckle structure at the fibre output significantly decreases, as a result of a strong mode coupling in a fibre. Future study should be done to extend the method's measuring range and improve the accuracy of the measurements.

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