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Temperature-compensated fibre Bragg grating -based sensor with variable sensitivity

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ABSTRACT

In this paper a Fibre Bragg Grating (FBG)-based sensor device for strain measurement with adjustable full-scale sensitivity is proposed. Installation flanges of the sensor can be moved with respect to the internal fixed FBG sensing length in order to adjust the overall strain sensitivity and the full scale measurement range of the device. Thermal drift is compensated using a technique based on the thermal expansion of a solid block connected to the fibre, in the pre-stressed region outside the grating. Typical calibration curves are reported to illustrate the sensor sensitivity variation with the layout and temperature.

1. Introduction

In recent years Fibre Bragg Grating (FBG) sensors [1,2] have been used increasingly due to important advantages related to their light weight, small dimensions, durability and insensitivity to electromagnetic interference. Furthermore, they can be multiplexed and embedded in materials such as composites, without requiring cumbersome wiring. For these reasons, FBG sensors have established as a leading technology with respect to other competing traditional and fibre-optic-based technologies. In the last two decades, FBGs have been used to develop a large variety of sensors and related applications. Sensing devices have been developed for the measurement of different physical quantities including temperature [3], pressure [4], acceleration [5] or humidity [6,7]. One of the major fields of application consists in the monitoring of mechanical strains [8–10] for a range of purposes such as structural health monitoring [11] in diverse fields, such as aerospace, automotive, civil, energy, oil and gas industry.

The application of FBG-based sensors to strain monitoring has required suitable technological solutions, including mounting supports and packaging of the sensor, which are necessary for harsh environments [12,13]. In some of these solutions, the fibre with the inscribed grating is fixed (usually glued) to the sensor structure in two permanent positions, and often pre-tensioned in order to measure both positive and negative strain values. In all these cases, the fixed position of the sensing fibre with respect to the sensor package determines the sensitivity and consequently the measurement range of the sensor. In order to extend the application potential, a different solution is proposed in this paper. In particular, mobile mounting supports are devised in order to be able to adjust the sensitivity to the preferred value.

Different solutions have also been reported in the literature to compensate the undesired sensor sensitivity to temperature, for example by means of a strain-free fibre Bragg grating [14] or automatically [15,16]. Most of these concepts are more suitable for surface-mounted or embedded FBG sensors than for those housed in a protective steel body. For this reason, a technique using a load-free element connected to the fibre in the proximity of the pre-tensioned fibre Bragg grating was considered and developed in this work. Since the drawback of such a device consists in its intrinsic weakness to shocks and vibrations, the proposed solution was improved by using a damping fluid.

In this paper, firstly the basic principle of FBGs operation is described briefly. Then, the concept and design of the newly-developed temperature compensated FBG strain sensor are presented. Finally the results of static tensile testing and temperature calibration of the sensor are reported and discussed.

2. Sensing principle

A Fibre Bragg Grating is a periodic modulation of the effective refractive index n_{eff} in the optical fibre core. Light travelling at the Bragg wavelength, λ_B, which is a grating feature, is reflected back

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by the grating itself and, as a result, is missing in the transmission spectrum.

The principle of operation of a Fibre Bragg Grating is illustrated in Fig. 1. The reflected spectrum is centred in the Bragg wavelength, which depends on the mentioned effective index of refraction and on the Bragg period (Λ_B) of the grating, according to the following Bragg equation:

$$\lambda_B = 2n_{eff}\Lambda_B \tag{1}$$

When a local deformation is present, the period of the grating varies and the reflected wavelength changes accordingly, allowing detection of the local strain via the Bragg Eq. (1). Strain and wavelength variations can be expressed by a one-to-one relationship only in the case of unidirectional deformation, provided that the effect of the temperature on the Bragg wavelength is suitably compensated. The wavelength shift with respect to temperature is obtained by differentiating Eq. (1) with respect to temperature:

$$\Delta\lambda_B = 2\left(n_{eff}\frac{\partial\Lambda_B}{\partial T} + \Lambda_B\frac{\partial n_{eff}}{\partial T}\right)\Delta T \tag{2}$$

It can be seen that a temperature increase causes a thermal elongation of the grating and therefore a change of both the Bragg period and the refractive index. When the temperature change is small, Eq. (2) can be re-written as [17]follows:

$$\Delta\lambda_B = \lambda_B(\alpha_f + \alpha_n)\Delta T = \lambda_B\beta\Delta T \tag{3}$$

where $\alpha_f = \frac{1}{\Lambda}\frac{\partial\Lambda_B}{\partial T}$ is the thermal expansion coefficient of the optical fibre, which is approximately $0.55\times10^{-6}\,\mathrm{K}^{-1}$ for silica, and $\alpha_n = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T}$ is the thermo-optic coefficient, which is dependent on the type and concentration of the dopants.

Values between 3.0×10^{-6} and $8.6\times10^{-6}\,\mathrm{K}^{-1}$ for a germanium-doped, silica-core fibre have been reported in the literature [1]. The coefficients α_f and α_n can be combined in the temperature coefficient β. Linearity of Eq. (3) holds only for small temperature variations due to the fact that the thermo-optic coefficient is also temperature dependent. For higher values of the temperature, the equation becomes nonlinear and a polynomial interpolation is necessary.

3. Sensor device concept and design

The sensor proposed in this work is depicted in Fig. 2. The optical fibre (denoted by ‘2’ in the figure) with the Bragg grating (8) is suitably pre-tensioned and fixed to a cylindrical steel body

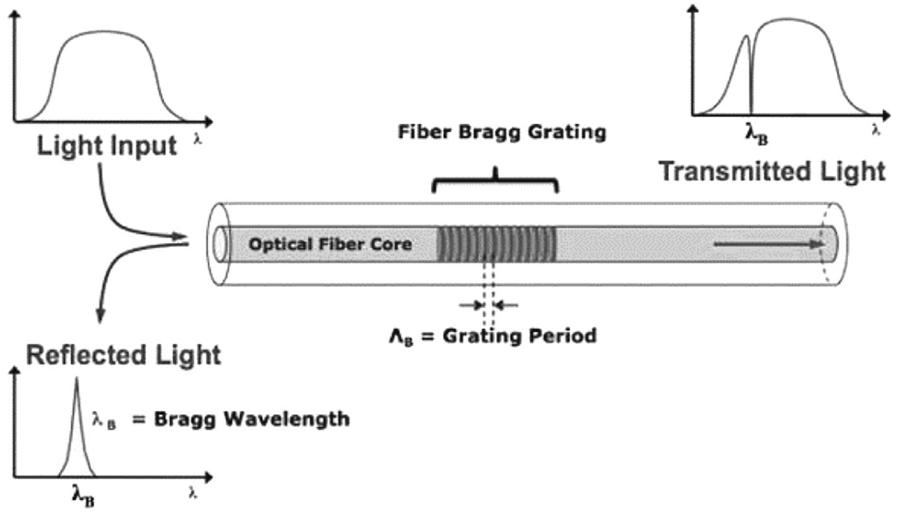

Fig. 1. Fibre Bragg Grating's principle of operation.

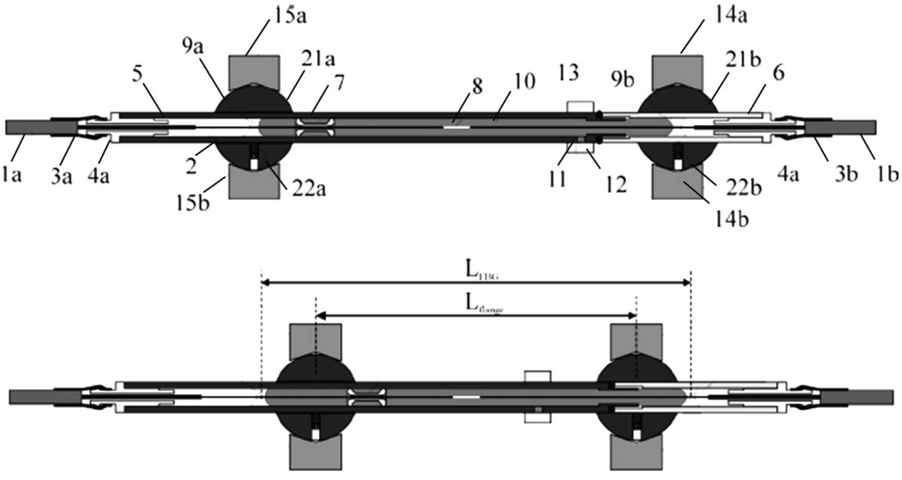

Fig. 2. Sensor drawings with different positions of the flanges.