


Dynamic strain measurements using embedded fiber optic sensors

Helmut Woschitz and Fritz K. Brunner

Abstract

Engineering geodetic monitoring has reached a very high level of maturity and provides information with millimetre accuracy. However, these measurements have low data rates and are naturally limited by the surface of the objects, e.g. buildings. The use of embedded sensors, especially fiber optical sensors (FOS), can provide important information about the inside behaviour of an object, even continuously. This information is used in structural health monitoring (SHM) to assess the health state of a building, which is a rather new but significant development.
Several fiber optic (FO) instruments are commercially available. They offer high precision, e.g. some micrometres or even some nanometres for measuring changes in length, and high data rates, e.g. 1 kHz. In this paper, two FO measuring systems for dynamic strain measurements are presented and two novel applications are described.

Keywords: fiber-optic measurement systems, dynamical measurements, long gauge SOFO sensors, FBG sensors

Kurzfassung

Das ingenieurgeodätische Monitoring hat einen hohen Reifegrad erreicht und liefert großräumige Informationen mit Millimeter-Genauigkeiten. Allerdings liegen diese Messungen zumeist nur niederfrequent vor und können auch nur an der Oberfläche der Objekte (z.B. Bauwerke) durchgeführt werden. Im „Structural Health Monitoring" (SHM) werden Sensoren in das Bauwerk integriert, womit Informationen aus dem Inneren eines Objektes zugänglich werden. Dafür gibt es auch mehrere faseroptische Sensoren (FOS) mit wichtigen Vorteilen, z.B. elektromagnetische Immunität, geringe Größe, Multiplexing, hohe Messpräzisionen und Abtastraten von mehreren 100 Hz. Daher wurden 2001 am Institut für Ingenieurgeodäsie der TU Graz als neues Forschungsthema FOS und deren Anwendungen für die Ingenieurgeodäsie aufgegriffen. In der vorliegenden Arbeit werden zwei FOS beschrieben und deren Anwendung in zwei neuen Projekten vorgestellt. Mit beiden Systemen können Längenänderungen zwischen zwei Ankerpunkten mit sehr hoher Präzision und relativ hohen Abtastraten bestimmt werden.

Schlüsselwörter: Faseroptische Messsysteme, dynamische Messungen, langarmige SOFO Sensoren, FBG Sensoren

1. Introduction

Geodetic monitoring of structures and the determination of deformations has reached a high level of maturity considering the instrumental as well as the analysis developments. Here structures stands for large civil engineering structures like bridges or dams, and natural objects like slopes. But classical geodetic instruments rarely provide high data rates. For example, geodetic deformation surveys with total stations are usually carried out at certain repeat times, e.g. annually for dams or with periods of some hours or even minutes for individual monitoring projects. During the past 20 years GPS measurements have been used to continuously measure deformations with very high precision of several millimetres. However, all geodetic measurements are restricted by the surface of a structure and thus the results rather describe the external deformation of a structure, [1]. But on a global scale – global refers here to the structure and its surroundings – the geodetic data are extremely important as they are the sole source of information about the integral behaviour of a structure.

The use of embedded sensors can overcome the barrier of the structure's surface for geodetic measurements. Embedding sensors is of course possible during the construction of a new building otherwise the sensors have to be applied to the structure's surface. For this purpose fiber optic sensors (FOS) have emerged as the most useful sensor type. FOS have also unique properties, e.g. electromagnetic immunity, long term stability, small dimensions or multiplexing availabilities. The optical fibers can be used as sensors as well as for the transmission of the signals which allows the analysis unit to be quite distant to the measurement site. The generic term for deformation studies is Structural Health Monitoring (SHM), and the civil engineering aspects are treated under the term Civil Structural Health Monitoring (CSHM). The international organisation for CSHM is ISHMII (International Society for Structural Health Monitoring of Intelligent Infrastructure). ISHMII is about to launch its international journal (JCSHM) published by Springer Verlag, [2]. Two recent book releases clearly indicate that SHM using embedded fiber optic sensors has also reached a mature level, [3] and [4].

A few years ago the Department of Engineering Geodesy and Measurement Systems (EGMS) of the Graz University of Technology started a serious build-up of FOS equipment and practical applications. This initiative started with the investigation of a monolithic concrete deck using embedded FOS of the SOFO type and geodetic measurements, [5]. Recognising the unique capability of geodetic measurements to provide global data, the proposal has been made to combine sporadic geodetic with continuous FOS measurements for an advanced health monitoring system of structures, [6]. Recently a study of a fiber optical tiltmeter was completed, [7], and a novel calibration facility of FOS has been developed. However, in this contribution two applications of FOS will be presented where dynamical measurements of strain values are essential. In the first application, long gauge fiber optic sensors (5 m length) were used for the measurement of a large geotechnical structure, in the second Fiber-Bragg-Grating sensors (5 mm length) were used to determine the deformations inside of a rather small structural element.

2. Dynamical long gauge fiber-optic SOFO system

2.1 Principle

The SOFO measurement system (produced by Smartec, Switzerland) works with low-coherent light and two separate interferometers, [8]. The SOFO sensor is the first interferometer and consists of two monomode glass fibers which are laid out in a protective hose. One fiber which is under tension is the measurement fiber (red, fig. 1), and the other fiber, the reference fiber, is loosely spun between the anchors (green, fig. 1). Thus the temperature compensated change of the length between the anchors can be measured. The sensor may be stretched about +1.5% and shortened by −0.5% during deformation. It can be embedded in the material of the structure and may be operated by the SOFO Static or the SOFO Dynamic reading unit, [9]. For the SOFO Dynamic a Mach-Zehnder interferometer, [10], is used for the demodulation of the signal. Fig. 1 shows the principal components of the system.

The phase-modulator located in one branch of the Mach-Zehnder interferometer can be

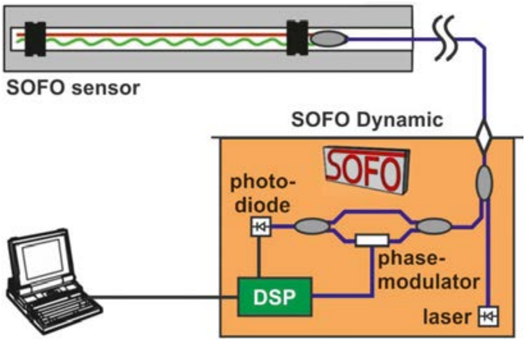

Fig. 1: Schema of the SOFO Dynamic system using a Mach-Zehnder interferometer and a DSP (digital signal processor) unit, after [10]

operated with 50 kHz. Up to 8 SOFO sensors can be used simultaneously by splitting the light of the laser-diode and dedicating a Mach-Zehnder interferometer to each sensor. Smartec claims a resolution of 10 nm and 1 kHz which is fully confirmed by our own experiments, [11]. The use of a phase-modulator in the Mach-Zehnder interferometer realises a high frequency resolution of length changes, however, only relative distance changes can be measured. Using the same sensors but another reading unit (SOFO Static), absolute measurements may be performed (2 µm precision, approx. 0.1 Hz).

2.2 Application: Large Strain-Rosette

On alpine slopes, deep-seated gravitational creep is a frequently observed phenomenon. However, the causes and mechanisms of these landslides are insufficiently understood for the prediction of motions. Thus we have developed a GPS monitoring system, [12], and use this system since 1999 for monitoring the landslide “Gradenbach”, Austria.

The GPS monitoring results show that the motion of the mass movement is not uniform but rather intermittent, i.e., periods of accelerated motions (velocities up to 2 m/year) are followed by quiescent periods, [13]. However, GPS surveys are not sufficiently precise and fast enough to allow for a detailed study of this pattern of motions. But very precise dynamic measurements of the local strain situation could yield an insight into the geomechanics of this behaviour of a landslide which is required for the prediction of the landslide’s motions. Therefore, we have developed an embedded strain rosette for dynamic in-situ measurements of local distance changes. The concept and the results of a test installation were shown in [14]. The strain rosette consists of three 5 m

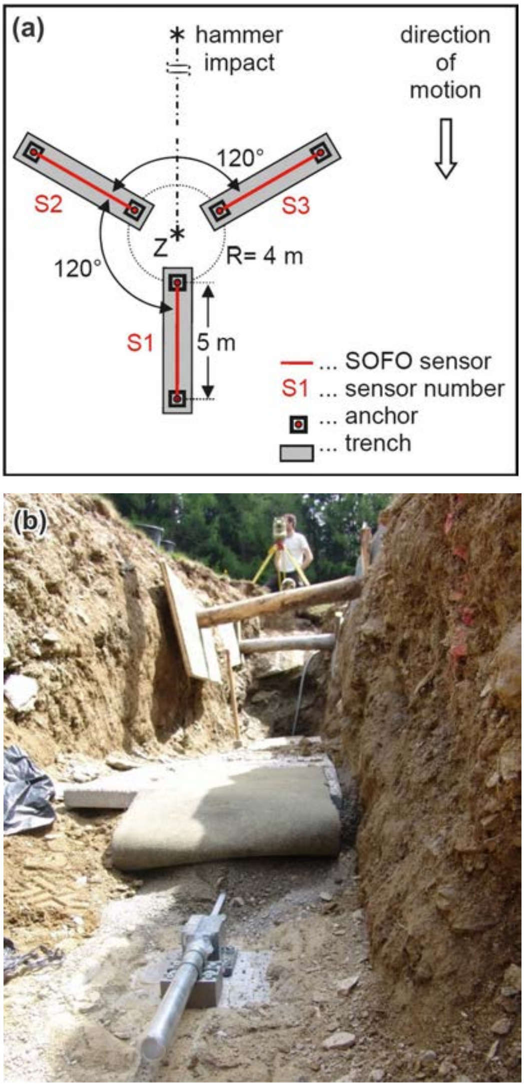

Fig. 2: (a) Schema of the strain rosette, (b) sensor S2 whilst embedding

long extensometers at a separation of 120° in orientation. The extensometers are long gauge fiber optical sensors of the SOFO type.

Fig. 2a shows a schema of the strain-rosette. Each sensor was embedded in a separate trench at a depth of about 2 m (fig. 2b), where it was attached to two concrete anchors of 0.5 m length and 0.3 m diameter. The main challenge of embedding the sensors was their proper connection with the rock material, [15].

At the landslide area, mass movements cause micro-earthquakes, which occur approximately once a week and have duration of less than 0.1 s (E. Brückl, personal communication). The exact relationship between these micro-earthquakes and the mass movement is rather unknown. It is one of the purposes of the strain rosette to detect possible strain waves associated with the Gradenbach deep-seated mass movement.

In order to investigate the capability of the strain rosette to measure strain waves, artificial excitations were used. The strain variations were generated by hammer (5 kg) impacts to the ground and data were acquired with the SOFO Dynamic reading unit with a sampling frequency of 1 kHz. First experiments have shown very small signal amplitudes, e.g. 0.14 µm for hammer impacts 5 m away from the strain rosette's centre Z. With increasing distance, they even get smaller due to energy dissipation and absorption in the soil and they quickly get down to the noise level of the measuring system. Thus, at each point, 16 consecutive hammer impacts were performed and the signals were time-stacked. The experiment comprised hammer impacts at various distances and orientations from Z. Fig. 3 shows the signals (relative movement dL of the anchors of sensor S1) of the 16 impacts carried out at a position 155 m away from Z and their averaged signal.

The noise level of the system is $s_{dL} = 0.4$ nm and at this distance the amplitudes of the signal

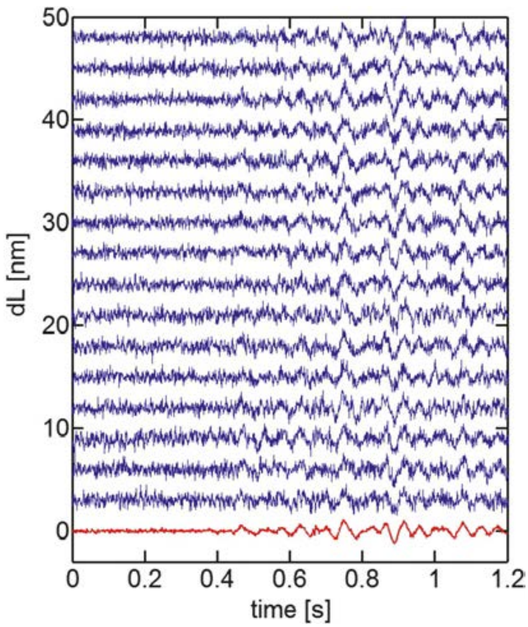

Fig. 3: Strain variations generated by 16 consecutive hammer impacts (blue line, time stacked and shifted for 3 nm to each other) and their mean (red) measured with sensor S1 at a distance of 155 m away from the strain rosette's centre

are as small as about 1 nm. This highlights the very high resolution of the measured strain variations using the SOFO Dynamic reading unit and the strain rosette. Other experiments have confirmed the high reproducibility of the signals which is in the nanometre range.

Using this highly sensitive measuring system, we now hope to find the signals of the rare micro-earthquakes. However, until now, we could only detect a regional earthquake (magnitude ML = 1.4; epicentre in Serbia; signal amplitudes at strain-rosette of 0.3 nm), see [15].

3. Fiber-Bragg-Grating Sensors

3.1 Principle

The principle of Fiber-Bragg-Gratings (FBG) sensors is shown in fig. 4. A light-source emits band limited light, which is transmitted into the direction of the FBG using an optical fiber. The FBG consists of periodic changes ($10^{-6} < \Delta n < 10^{-2}$) of the core's refractive index n, see [16] for example.The FBG reflects one portion of the light (λ_B) which corresponds to

$$\lambda_B = 2n\Lambda_B \tag{1}$$

where n is the refractive index and Λ_B is the grating period.

The remaining parts of the light are transmitted along the fiber until they meet another FBG, where another portion of light is reflected. This allows to place several tens or even more than hundred sensors on one single fiber. The reflected signal travels back and is split by an optical coupler into two parts, with one part travelling to the spectrometer. There, its wavelength λ_B is detected. If strain is applied to the FBG, primarily the grating period Λ_B will change and as a consequence, λ_B of the reflected light will be shifted. Thus, the applied strain can be determined with a resolution of about 1 με by measuring the wavelength shift $\Delta\lambda_B$. The unit micro-strain [με] is commonly used in FOS applications and equivalent to the well-known [ppm] in geodesy:

$$1\left[\mu\varepsilon\right] = \frac{\Delta L}{L} \cdot 10^{-6} \tag{2}$$

The Bragg-wavelength λ_B also depends on n, see eq. (1), and thus λ_B is also sensitive to temperature. If absolute strain values are necessary, the measurements must be corrected for temperature induced wavelength shifts. For this purpose, a FBG-based temperature sensor may be used, where the grating is shielded against mechanical strain. The strain and temperature sensitivities of a typical FBG sensor are ([17], p. 127):

$$\frac{1}{\lambda_B} \cdot \frac{\Delta\lambda}{\Delta\varepsilon} = 0.78 \cdot 10^{-6} \,/\, \mu\varepsilon \tag{3}$$

$$\frac{1}{\lambda_B} \cdot \frac{\Delta\lambda}{\Delta t} = 6.678 \cdot 10^{-6} \,/\, \mathrm{K}$$

The sensitivities given in eq. (3) are reduced for λ_B because of the dispersive characteristics of glass and they may vary for different fiber types. Using a modern instrument with an optical resolution of 1 pm, strain and temperature may be acquired with a resolution of 0.8 με and 0.1 K respectively.

Several instruments are commercially available. Some of them provide sampling rates up to several kHz and allow the simultaneous measurement of all connected FBGs. There is also a variety of FBG based sensors available, either ready-for-use sensors in standard applications or bare fiber sensors for most flexibility in special applications.

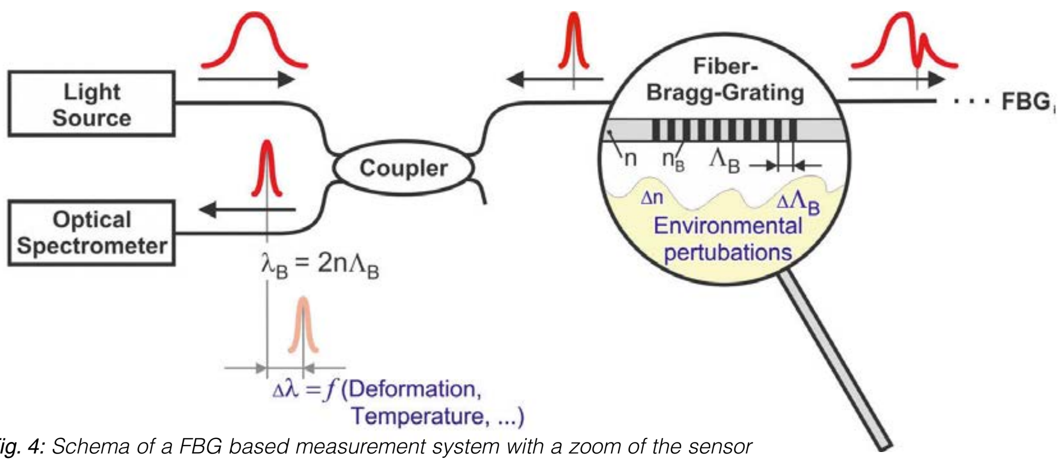

Fig. 4: Schema of a FBG based measurement system with a zoom of the sensor

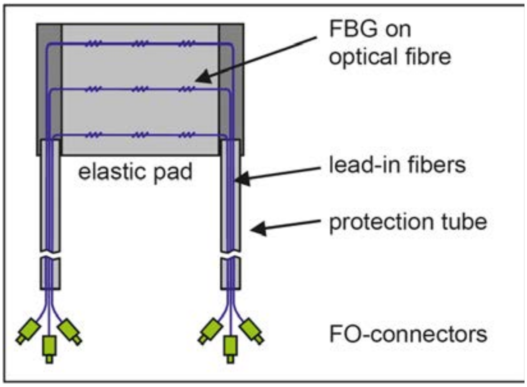

Fig. 5: Schema of the rail-strain-pad

3.2 Application: Rail-Strain-Pad

Elastic pads are used in railway engineering to reduce the stress in the roadbed and track components. In Austria, these pads need to be replaced after very short time spans (every 2.5 to 4 years, [18]), especially in the alpine regions. The reason for the short replacement time is rather unknown. Thus, investigations should be performed with strain measurements inside the elastic pad during the passage of trains. As the pads are rather small (e.g. $160 \times 150 \times 7$ mm^3), FOS appeared to be the only suitable sensor type. The optical fiber has small dimensions (e.g. 0.25 mm diameter) and when using FBG sensors, several sensors can be integrated into one single pad. However, the signals of individual sensors must not overlap in order to separate them correctly. Because of the large horizontal deformation during a train passage (about 2 % to 3 %), three sensors placed on a single fiber. Using three fibers and an instrument with several input lines, it was possible to integrate 9 sensors into one elastic rail-strain-pad, see fig. 5.

Draw tower gratings, [19], of 5 mm length were used, as this FBG sensor type provides a higher mechanical resistance compared to recoated sensors. In order to get the most reliable results, the fibers were integrated into the material matrix of the elastic pad during its production.

For testing and calibration purposes, the rail-strain-pad was put on a test facility used for applying pressure. The passage of a passenger train (heavy engine, 6 wagons, velocity of 140 km/h) was simulated, loading the pad by the corresponding known vertical forces. Fig. 6a shows these forces, which vary in between 18 kN (i.e. the clamping force of the rail clamps which hold the rail at the sleepers) and 65 kN. Exemplarily, the strain measured by the three sensors A to C on the middle fiber (see fig. 6b) is shown in figs. 6c-e.

Note that the FBG sensors are arranged eccentrically inside this rail-strain-pad. The measured strain values are quite different for the three sensors, indicating that the strain distribution inside the pad is quite nonlinear. Sensor A, which is the outmost of the three sensors, shows the largest strain values (up to 1500 $\mu\varepsilon$). Sensor C, which is 10 mm closer to the pad's centre, provides strain values that are smaller by a factor of 7. In the central region of the pad (sensor B), even negative strain ($-20\ \mu\varepsilon$) appears, indicating that the pad is compressed in this region. This performance was previously unknown.

It is now one of the next goals to compute the forces applied to the rail-strain-pad using the

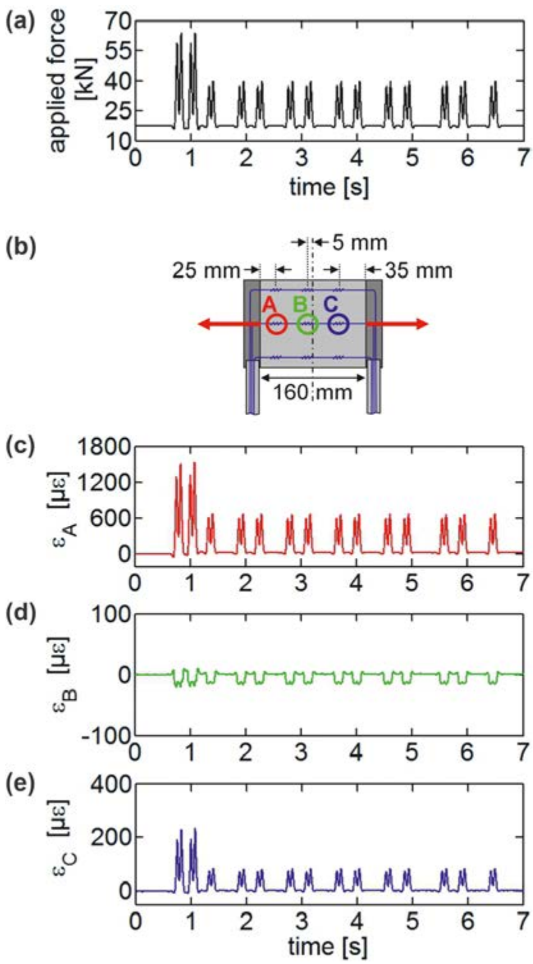

Fig. 6: Simulation of a train passage with (a) the vertical forces applied by a test facility, (b) the location of the FBG sensors inside the rail-strain-pad and the strain measured by (c) sensor A, (d) sensor B and (e) sensor C

FBG signals and individual calibration functions for each sensor. First results were already shown in [20].

4. Outlook

Two novel examples of embedded FOS for the dynamic measurement of strain are presented: (i) large strain rosette and (ii) rail-strain-pad. The large strain rosette consists of three 5 m long SOFO sensors which are embedded in the rock material of a landslide mass. The attainable precision is better than 2 nε with 1 kHz. The strain rosette will now be used to study the Gradenbach landslide in order to detect precursors of accelerated and decelerated motions of the landslide. The rail-strain-pad was developed for the study of forces acting on the elastic pad during train passages. Here the fiber optical sensors FBG are embedded in the pad and the results of this study will be used in a new the design of the pad's material.

These two examples show the implantation of FOS in existing structures of different size, and the latter the embedding of the FOS when the structure is being built up. Both examples have shown the potential of the fiber optic instruments used, especially for dynamic measurements. SHM is a growing discipline with many new applications and thus new FO instruments with enhanced performance or even new functionality will be available in the future.

Acknowledgements

The strain rosette shown in this paper is part of a research project funded by the Austrian Academy of Sciences as part of the Austrian contribution to ISDR. The development of the rail-strain-pad was supported by the FFG in cooperation with Getzner Werkstoffe GmbH (DI P. Burtscher, DI M. Dietrich).

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