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Design and field testing of a fiber optic pressure sensor for underground water level monitoring

Luca Schenato[a], Juan Pablo Aguilar López[b], Andrea Galtarossa[c], Alessandro Pasuto[a],
Thom Bogaard[b], Luca Palmieri[*c]

[a] Research Institute for Geo-Hydrological Protection, National Research Council, Padova, Italy;
[b] Department Water Management, Delft University of Technology, Delft, The Netherlands
[c] Department of Information Engineering, University of Padova, Padova, Italy.

ABSTRACT

The paper illustrates the design and field test of a rugged FBG sensor prototype for high-sensitivity measurement of groundwater level (GWL) variations. Pressure sensors have many fields of application, ranging from environmental monitoring to the oil and gas industry. In particular, pressure sensors can be used to monitor the stability of dikes and embankments by measuring the inner phreatic level at their foot to detect anomalous filtration and excess of pore pressures. For this application, rather high sensitivity at an affordable cost is required. In recent years, fiber optic pressure sensors have been explored with different solutions, but the technologies proposed so far have either small sensitivity and hence are befitted for large pressure ranges, or are based on interferometry and hence require rather expensive laser sources. The sensor described in this paper exploits a 3D-printed mechanical transducer to convert external pressure in longitudinal strain along the fiber. A second FBG, embedded in the sensor, is used to compensate for temperature cross-sensitivity. The structure is enclosed in an aluminum alloy case to withstand harsh environments and installation procedures. Pressure and temperature sensitivities of the sensor are about $20\ pm/cm\ H_2O$ and $17\ pm/°C$, respectively. Three sensors of this type have been successfully tested in a large scale dike at the Flood Proof Holland facility, in Delft, Netherlands.

Keywords: fiber optic sensor, pressure, groundwater level variations, Bragg gratings, 3D printing

1. INTRODUCTION

Pressure measurements are of large interest and, in the last decades, different fiber optic pressure sensors have been devised and studied. All the most common optical sensing approaches have been explored, including those based on intensity, phase and wavelength measurement. The simplest approach is based on the measurement of pressure-induced losses [1]. However, the simplicity of these sensors comes at the expense of low accuracy and slow response time. Differently, interferometric pressure sensors, among which those based on Fabry-Perot interferometers (FPIs), offer the highest sensitivity and fast response times. Nonetheless, they are not easy to multiplex and require very stable laser sources, which makes them expensive. Also, fiber Bragg gratings (FBGs) can be used to measure pressure; however, its bare sensitivity (mainly related to the Poisson ratio of silica) is approximately $-3 \times 10^{-3}\ nm/MPa$ [3], so faint that FBGs can be used only at GPa-level pressure.

A general approach to enhance sensitivity can be to couple the optical sensor with a mechanical transducer. For example, FPI-based sensors often exploit a membrane or a diaphragm as one of the FPI reflecting surfaces, thus linking the sensitivity to the elastic properties of the membrane. In a similar approach, the membrane deformation can be monitored by fiber Bragg gratings (FBGs) [2]. Alternatively, the FBG can be embedded into a thick layer of a polymer with high Poisson's ratio [4-6], which can exert a significant longitudinal strain to the FBG even under low pressure. Despite the intense effort, most of the FBG-based sensors proposed so far does not satisfy the requirements of many pressure applications, such as liquid level monitoring [7] and measurement inside soil levees and embankment for anomalous filtration detection [8], where very high resolution and accuracy are desired.

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[*] luca.palmieri@dei.unipd.it

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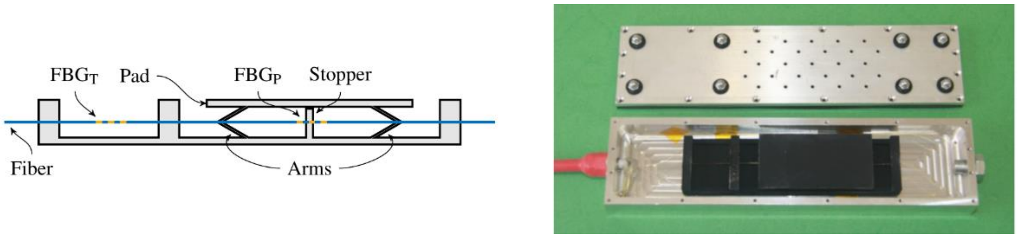
In this paper, the design, characterization and field-testing of a rugged FBG sensor prototype, capable of measuring underground water level for dike monitoring is described. The sensor, which is an evolution of a previous one [9], is based on a 3D-printed mechanical transducer that efficiently converts pressure into strain along the FBG. A second FBG, mechanically decoupled from the structure, is used to compensate for the intrinsic temperature cross-sensitivity. Field tests confirmed the viability of such approach.

2. DESIGN AND CALIBRATION

The sensor has been designed to target a resolution of a few centimeters of water column, which is deemed necessary to effectively monitor dikes stability by measuring the GWL variations. The sensor consists of two FBGs, one mechanically coupled to the transducer to sense pressure, the other decoupled from the transducer to monitor temperature and compensate its cross-sensitivity. As shown in Fig. 1(a), the pressure-transducing mechanism consists of a hexagonal pantograph, made by additive manufacturing (HP Multi jet-fusion technology with HP 3D High Reusability PA12 plastic). The structure is traversed by the optical fiber housing the two FBGs; in particular, the pressure FBG is installed inside the pantograph and the fiber is cemented at its wedges. In this way, any pressure acting on the top pad of the pantograph (which is exposed to the external environment) is converted in a strain along the FBG. The temperature FBG is housed in a second chamber, next to the pantograph. Since the sensor is intended to operate at around 10-15 °C and was assembled at around 20 °C, the fiber section traversing the pantograph was pre-strained to compensate the shrinkage of the structure at a lower temperature. Differently, the fiber section with the temperature FBG was not pre-strained to minimize mechanical coupling. The active part is installed inside a watertight aluminum case [Fig. 1(b)], tough enough to withstand the installation process. Pressure coupling to the external environment occurs through a set of holes drilled in the top cover of the case, above the pantograph. A thin rubber sheet (0.5 mm of thickness) acts as both case seal and pressure-sensitive flexible membrane.

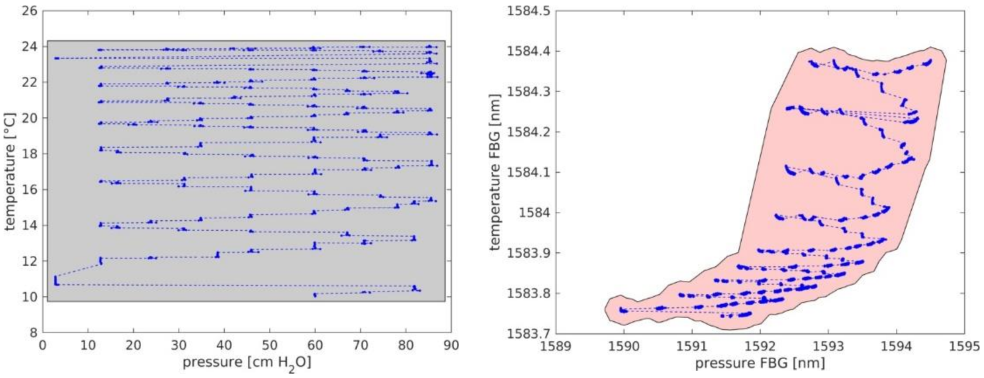


(a) (b)

Figure 1. (a) Sketch of the mechanical transducer. (b) Mechanical transducer and aluminum case.

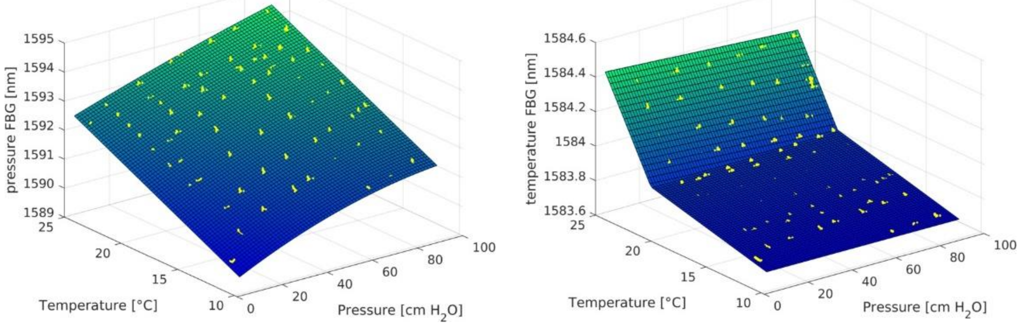
The sensors were calibrated with respect to pressure and temperature with a system of communicating vessels. Specifically, sensors were installed inside a plastic jar that was connected by a hose to a second jar, which acted as a water reservoir. By changing the height of this reservoir we could control the pressure applied to the sensors. The calibration procedure started with chilled water (around 8-10 °C) and continued until the water naturally reached room temperature (around 25 °C). The actual pressure and temperature were measured with a high-resolution I2C/SPI digital pressure/temperature probe (TE Connectivity, MS5803-02BA). In this way it has been possible to expose the sensors to useful ranges of pressure and temperature, as shown for example in Fig. 2(a); the corresponding wavelength shifts measured on the two FBGs are shown in Fig. 2(b). These sets of measurements were used to build the calibration surfaces of the sensors. Specifically, the response of the sensor is modelled by two 2-variate functions, describing the wavelength shift of each FBG with respect to both pressure and temperature. The model function $f_P(P,T)$ of the pressure FBG is polynomial, quadratic with respect to P and linear with respect to T. The result of the least square error (LSE) interpolation, in case of pressure FBG, is shown in Fig. 3(a), where yellow dots represent the measured data (only those above the surface are shown). The analogous result for the temperature FBG is shown in Fig. 3(b). As by design, this FBG is decoupled from pressure; nevertheless, it is still coupled to the thermal expansion of the structure, because it was not sufficiently loose. As it is clear from Fig. 3(b), the temperature FBG has two working regimes: below a certain temperature the FBG is not strained and its response is driven by the thermo-optic effect; above that threshold, the thermal expansion of the active structure is such that the FBG is no longer loose and its response becomes steeper, because driven by the thermal expansion of the active structure. This effect has been modelled with two intersecting planes, whose coefficients were determined by LSE fitting.

The partial derivatives of the interpolating functions $f_P(P,T)$ and $f_T(P,T)$ provide the sensitivities and cross-sensitivities of the two FBGs to pressure and temperature. The pressure sensitivity of the pressure FBG is about $20\ pm/cmH_2O$, while its cross-sensitivity to temperature is about $190\ pm/°C$. The temperature sensitivity is about $17\ pm/°C$ below $20\ °C$ and about $131\ pm/°C$ above. The calibration surfaces are obtained by numerically inverting the 2-dimensional 2-variate function $\boldsymbol{f}(P,T) = [f_P(P,T), f_T(P,T)]$. The products of the sensitivities with the corresponding interpolation residuals provide an estimate of the sensor accuracy, which is about $5\ cm$ and $0.5\ °C$.



(a) (b)

Figure 2. (a) Domain of the stimuli applied during the calibration. (b) Corresponding responses.



(a) (b)

Figure 3. (a) Response of the pressure FBG. (b) Response of the temperature FBG.

3. FIELD TEST

The main aim of the large-scale test was to evaluate the performance of the sensors in field conditions (real scale dike) for several days. The selected test site was a real scale dike located in the Flood Proof Holland dike testing facility, which allows simulating the boundary conditions of dikes expected during flood events by filling the basin adjacent to the monitored dike. One barometric pressure sensor and five water pressure devices (Divers, Van Essen inc) were installed inside standpipes as references, as shown in Fig. 4. The piezometer standpipes were aligned perpendicular to the longitudinal axis of the test dike. Three fiber optic pressure sensors were buried next to piezometers P1, P3 and P4 (see Fig. 4) at approximately the same depth. The installation of the sensors was made one month in advance, before the large scale field experiment, to let the soil and sensors settle. The test basin was flooded and emptied in controlled cycles for several days, while the readings of the piezometers and the fiber sensors were recorded.

As an example, Fig. 5 shows the pressure measured by the sensor in position P4, compared with the corresponding piezoelectric reference. The trend measured by the two sensors show a good agreement; the difference between the traces can be attributed both to the inhomogeneity of the soil (sensors were installed half a meter apart from each other) and to the different installation methods (Divers were in open standpipes; fiber sensors were buried and thus behave as closed water pressure devices). The good quality of the results confirms the viability of the approach and the effectiveness of the fiber sensor for the monitoring of GWL variations and hence dike stability.

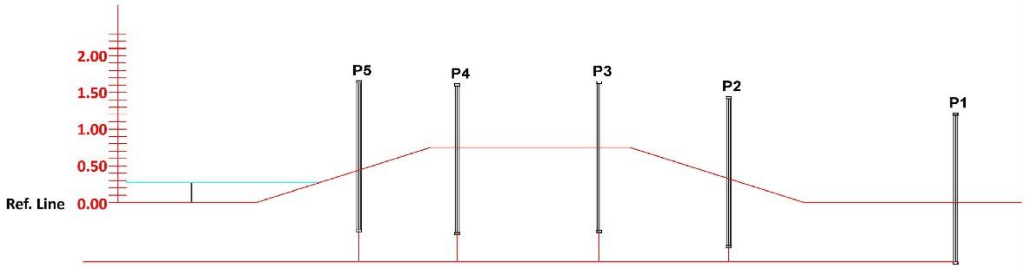


Figure 4. Schematic of piezoelectric reference sensors installation. Three fiber sensors were installed next to positions P1, P3 and P4.

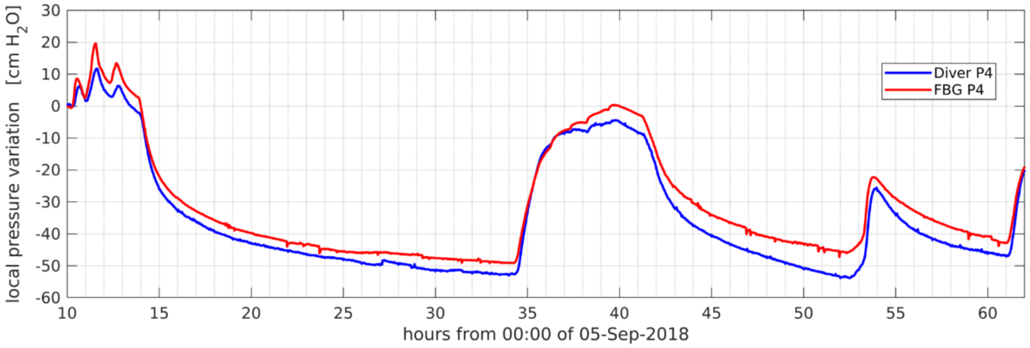


Figure 5. Response of the fiber pressure sensor compared with that of the corresponding piezoelectric reference.

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