Temperature-Corrected Determination of Mechanical Deformations in Geotechnical Structures Using Brillouin-Based Fiber Optic Sensors

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ABSTRACT

Structural Health Monitoring based on distributed Brillouin measuring techniques has been playing bigger and bigger role for applications in large-scale critical structures over the last decade.

The Brillouin sensing techniques make use of low-loss single-mode optical fibers as distributed sensors allowing compound strain and temperature profile discrimination along the measured section even over several tens of kilometers. Thereby, the measured Brillouin frequency shift (BFS) features much stronger dependence on the longitudinal strain in the sensor fiber than on the temperature distribution along the fiber optic sensor. By detection of slight structural changes in monitored civil structures, such as dams, pipelines and tunnels, the influence of temperature on the measured BFS cannot be neglected.

In simple cases of fiber optic sensors embedded deeply enough into earth structures no significant temperature gradients caused by weather conditions such as sunrays could be observed. The temperature contributes here only to the signal offset and the local mechanical deformations arisen due to soil displacement can be read directly from the distribution of the BFS. Also special cable solutions for separate determination of temperature and strain have been tested by us under field conditions. The use of two separate optical fibers for strain and temperature detection limits the spatial resolution and measurement accuracy in the determination of both physical quantities.

In search of the optimal sensory solution for monitoring of mechanical deformations taking into account the temperature component in the measured signal the use of so called nonzero dispersion-shifted fibers has been investigated in several laboratory tests. Due to different doping concentration in the core new resonance acoustic modes can propagate in such optical fibers which results in multipeak structure in the Brillouin gain spectrum (BGS). The appearance of more than one resonance peak in the BGS offers the possibility to realize simultaneous measurement of longitudinal strain and temperature by analysis of applicable BFSs as function of both physical quantities using only one low cost optical fiber.

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INTRODUCTION

Distributed fiber optic sensors based on stimulated Brillouin scattering in glass optical fiber (GOF) are excellently suitable for the measurement of slowly-varying strain and temperature over a length of more than even 20 km. Such sensors of a diameter of less than 1 mm can operate in strong electromagnetic fields, under “harsh” explosive and chemical environments and under ionizing radiation. The available measurement systems based on Brillouin Optical-Fiber Time-Domain Analysis (BOTDA) [1,2] or Brillouin Optical-Fiber Frequency-Domain Analysis (BOFDA) [3,4] enable thereby the recording of distributed temperature and strain profiles along the monitored structure with a spatial resolution down to 0.5 m - 1 m.

In modern earthwork structures (railway and road embankments, dikes and dams) it is common procedure to embed geosynthetics like non-woven and grid structures into their soil bodies. These geosynthetic materials act as filters, reinforcement and drainage elements. They are also integrated for strengthening of the earthwork structures and prevention from surface erosion. By additional integration of distributed fiber optic sensors in the geosynthetics, “smart” fleece or grid mats can be realised [5]. The use of planar sensor carrier facilitates the detection of the mechanical deformations transferred into the sensor fiber in the form of the longitudinal strain.

In practice, apart from the above mentioned measurement capabilities, the wide implementation of sensing systems based on Brillouin scattering is often limited by the sensitivity of the measured variable, the so-called Brillouin frequency shift (BFS), to both strain and temperature. This physical property leads to some ambiguity of the measurement results, since the observed BFS can be caused by the change of strain or temperature.

In this paper, we present a field test under the aspects of simultaneous temperature and strain sensing using the distributed Brillouin sensors. We also discuss sensory utilization of optical fibers with modified refractive indices for Brillouin-based discriminative sensing of both mentioned physical quantities.

SENSOR PRINCIPLE

The use of all Brillouin-based distributed measurement systems is predicated on the determination of the spatially distributed Brillouin gain spectra (BGS) along the sensor fiber. Furthermore, the BGS is measured by coupling a pump lightwave into the sensor fiber and by observing the amplification of a weak counterpropagated probe signal coupled into the other end of the fiber. If the frequency shift between both optical signals is equal to the frequency of the acoustic wave excited during the Brillouin interaction in the sensor fiber, then the Brillouin gain is maximized and the mentioned frequency difference corresponds to the BFS. The value of BFS is thereby proportional to both the optical fiber's refractive index and the longitudinal acoustic velocity in the sensor fiber. Thus, due to a step-index profile for the most frequently used standard single-mode optical sensor fiber only one acoustic mode is enhanced effectively. That means, only one Lorentzian-shaped peak is observed in the BGS of single-mode optical fiber (SMF). The single BFS as a linear function of applied strain and temperature contains solely compound information about influence of both parameters on the measured signal. The characteristic coefficients of the BFS linear dependence on temperature and strain in the standard single-mode glass fibers could be quantified at a wavelength of 1.55 μm as 1.12 MHz/°C and 500.5 MHz/%, respectively. The direct comparison of the temperature C_T and strain C_ε coefficients indicates a leading influence of the strain on the measured frequency shift. Generally, the Brillouin-based distributed measurement techniques enable therefore temperature-influenced strain measurements.

Multiple resonances in BGS

The study of acoustic modal properties in optical fibers with different refractive indices shows a possibility to realize the Brillouin-based simultaneous temperature and strain measurement. Due to different doping concentration in the core of dispertion-shifted or dispertion-compensating fibers new resonance acoustic modes can propagate in such optical fibers. These longitudinal acoustic modes called guided leaky acoustic mode [6], with velocities that vary between those in the core and in the cladding, can also scatter light contributing to multiple resonances in BGS. Thus, we can observe than several BFSs corresponding to longitudinal acoustic velocities of appropriate leaky modes. The multiple resonances in BGS achieved by modifying the refractive index profile lead to the separate influence of temperature change ΔT and strain gradient Δε on every single resonance frequency shift BFS, given by:

$$\Delta f_B{}^i = C_\varepsilon{}^i \bullet \Delta\varepsilon + C_T{}^i \bullet \Delta T, \qquad (1)$$

where $\Delta f_B{}^i$ describes the change of the appropriate BFS due to applied Δε or ΔT.

From (1) it follows that a simultaneous measurement of temperature and strain applied to the sensor fiber can be already realized by measuring of two applicable $\Delta f_B{}^i$ in multiple structures of BGS, assumed that:

$$Det\ C \neq 0, \qquad (2)$$

with

$$C = C_\varepsilon{}^i \bullet C_T{}^j - C_\varepsilon{}^j \bullet C_T{}^i. \qquad (3)$$

The first laboratory tests on these new types of distributed Brillouin sensors are described separately below.

FIELD TEST

As shown in Figure 1 (left), in the framework of the German program RIMAX a sensitive textile structure with integrated standard optical cables as distributed sensors was embedded behind an earth dam in Solina (Poland) in 2006. The following control Brillouin-based measurements along a Nexans standard cable are summarized in Figure 2. The applied BFS as a function of location includes compound information about the temperature distribution and strain state of the standard fiber sensor. Assuming a constant temperature along the sensitive mat, then the temperature influence on the measured signal can be understood as a signal offset. The signal shift along the y-axis therefore points to different temperature during performing the individual series of measurements. The stable profiles of recorded BFS distributions tell us that no significant critical deformation in the form of the local strain change in the sensor fiber has appeared here.

Figure 1. Installation of sensitive non-woven mats with standard silica fiber sensors in Solina (left) and in Swinna Poremba (right) – Poland.

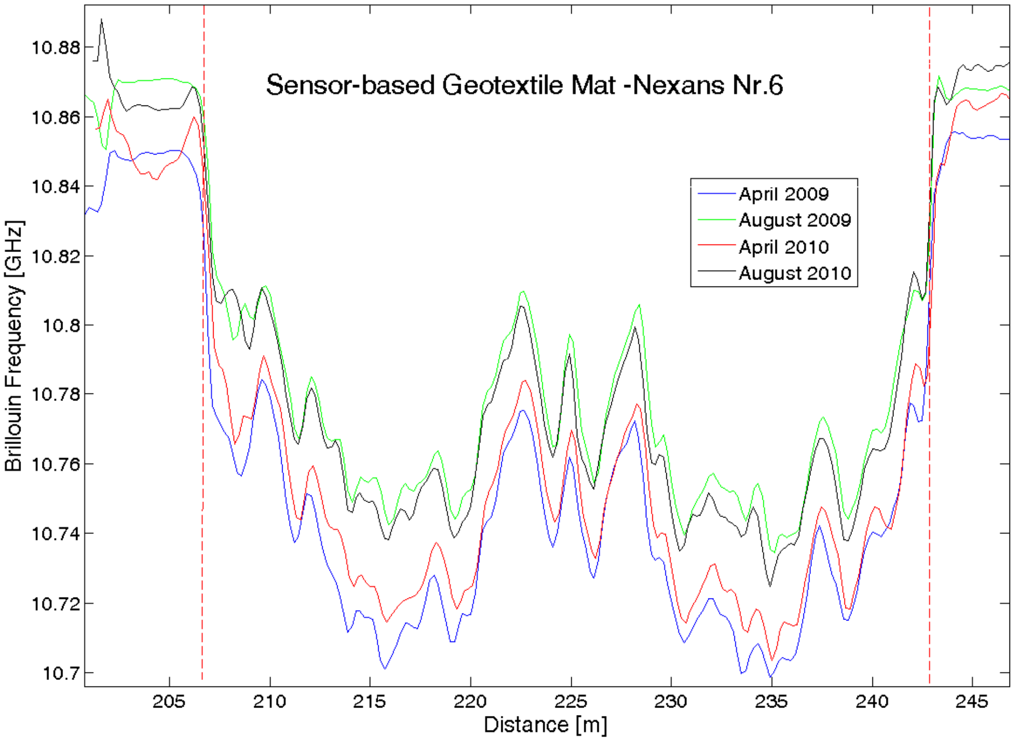

Figure 2. Spatial distribution of the Brillouin frequency shift along the Nexans standard cable. The sensitive mat with integrated sensor cable is located between 207 m and 243 m. The locally increased values of the measured frequency shift indicate a slight load of the distributed fiber optic sensor emerged during the integration of the cable into the mat and during the on-site installation.

If during the Brillouin-based strain measurements any constant temperature cannot be assumed, so special cable solutions like SMARTube or SMARTprofile (*smartec.ch*) for the separate strain and temperature sensing can be used. Such cables consist of one or two fibers protected from environmental influences exemplary placed inside a loose tube for pure temperature measurements, and one or two fibers exposed to mechanical strain. The cable profiles themselves provide good mechanical and technical resistance. However, the realization of the simultaneous temperature and strain measurement using such special cables requires the application of at least two sensor fibers. We believe that the use of only one fiber for the above-mentioned purpose offers a potential for increasing the measuring accuracy and improvement of the spatial resolution. Such a sensor solution using only one commercially available standard fiber cable could also improve the price efficiency of the distributed sensor.

LABORATORY TESTS FOR THE SIMULTANEOUS TEMPERATURE UND STRAIN SENSING

The aim of the investigation here is the realization of the temperature-compensated strain measurement using only one sensor fiber. Such an approach can lead to increased spatial resolution and to improved measurement accuracies.

Thanks to the laboratory tests performed on different GOFs with modified refractive indices the theoretically predicted multiple structures of BFS could be confirmed in practice. Figure 3 presents BGSs of two different dispersion-shifted fibers.

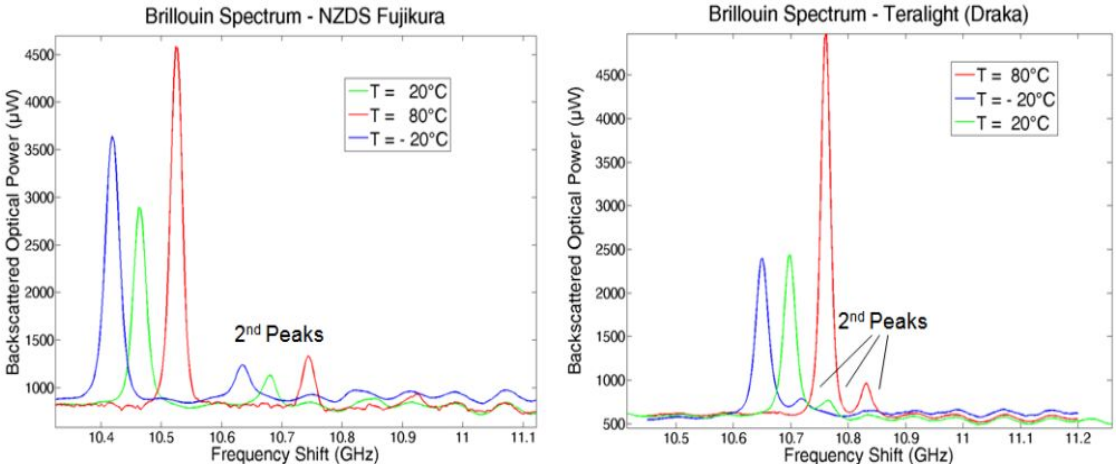

Figure 3. Brillouin gain spectra in two different non-zero dispersion-shifted fibers as a function of temperature. For the measurements performed at T = -20 ° C and T = 80 ° the optical pump power was increased by a factor of 2.

Under the aspects of measurement accuracy the secondary peaks observed in BGS should be characterized by preferably high amplitudes. This condition is fulfilled for the Fujikura fiber (see Figure 3). The combined strain and temperature measurements have also shown that the strain coefficients of the main and the secondary peaks were near equal. However, the corresponding temperature coefficients differed by 5% from each other. This in turn leads to the fulfillment of the condition (2), so that in principle the simultaneous strain and temperature measurement can be carried out using the proposed approach.

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