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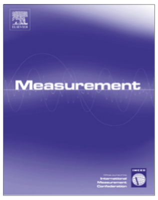

Experimental evaluation of a distributed Brillouin sensing system for measuring extensional and shear deformation in rock

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ABSTRACT

Distributed Brillouin sensing systems (DBSs) have growing applications in engineering and are attracting attention in the field of underground structures, including mining. The capability for continuous measurements of strain over large distances makes DBSs a promising monitoring approach for understanding deformation field evolution within a rock mass, particularly when the sensor is installed away from excavation damaged zone (EDZ). A purpose-built fiber optic sensing cable, a vital component of DBSs, was assessed in laboratory conditions.

A test program was performed to observe DBSs response to various perturbations including strain and joint movements, including opening and shearing of joints. These tests included assessment of the strain-free cable response and the application of extensional and lateral displacement to various sensing cable lengths (strained lengths), from 1 m down to 1 cm. Furthermore, tests were done to evaluate the time-dependent behavior of the cable and to observe the effect of strain transfer using a soft host material (e.g. a soft grout) under lateral displacement.

The noise level of the DBSs range was ±77 $\mu\varepsilon$, determined through repeated measurements on an unstrained cable. Stretching test results showed a clear linear correlation between applied strain and Brillouin frequency shift change for all strained lengths above half the spatial resolution of the DBSs. However, for strained lengths shorter than half the spatial resolution, no strain response was measurable and this is due to the applied internal signal processing of the DBSs to detect peak Brillouin gain spectrum and noise level. The stability with time of the measurements was excellent for test periods up to 15 h.

Lateral displacement test results showed a less consistent response compared to tension tests for a given applied displacement. Although the Brillouin frequency shift change is correlated linearly with the applied displacement in tension, it shows a parabolic variation with lateral displacement. Moreover, the registered frequency response (correlated with strain) of the system decreased significantly when the sensing cable was embedded in a sand-filled tube compared with direct cable displacement.

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1. Introduction

For many years, strain measurement in various engineering contexts has been done using point sensors such as strain gages. However, in large structures, point sensors cannot easily delineate the strain field on a large scale. A recently developed monitoring device called a distributed Brillouin-based sensing systems (DBSs), in conjunction with purpose-built fiber optic sensors, can provide continuous strain measurements along the length of a cable over large distances. This characteristic makes DBSs attractive to monitor large structures such as mines where the strain field is expected to be heterogeneous. DBSs sensors can also measure the temperature at the same locations, so they are appropriate for thermoelastic cases because the strain can be independently corrected for temperature.

DBSs were first used in the late 1980s to measure local attenuation in optical fibers [1]. Since then, they have been used for monitoring in different applications including electrical power lines [2], oil and gas pipelines [3], coiled tubing [4], concrete and steel bridges [5–7], composite structures [8], embankments and dams [9], and landslide and slope stability assessment [10]. They have also been applied to the monitoring of underground excavations including shallow tunnels [11] and underground mines [12].

Apart from a few field installations, such systems have been mostly used in experimental research to evaluate a specific parameter in comparison with more conventional sensors. Several studies have addressed measurement performance when the sensor is attached or embedded in a concrete beam under deflection [13–15], or to study pre-embedded defects in steel pipelines [16], composite pipes [17], and well casing [18]. Also, in a study with the same DBS as used in this study, validation of measured bending strain was evaluated in a number of long beams made of concrete, wood, and aluminum with different sensor attachment methods [19].

Microseismic events are common in deep underground mining as the rock mass responds to excavation operations. Such events are typically located close to excavation boundaries, but there have been large seismic events distant from mined-out regions, particularly as the extraction ratio increases [20]. Apart from near-field events that are known as stress-induced events, distant events cannot easily be explained by elastic field stress changes; deformation field variations caused by gravity-driven rock block movements may be a better way of explaining these events. Hence, to understand rock mass behavior around a mine, more distant deformations must be measured, and in this regard, distributed optical fiber sensors (DOFSs) may help understanding and modeling of three-dimensional load transfer mechanisms and rock mass response.

If a DBSs is to be installed in a deep underground mine to monitor the remote deformation field, proper characterisation of the sensing system performance and limitations before field installation is necessary. This article presents results from an experimental test program on the response of a DBSs, including longitudinal extension, lateral displacement, and measurements on unstrained cable for noise level assessment.

2. Background

2.1. DBSs working principles

When light is sent through an optical fiber, scattering causes losses. A small portion of the light is back-scattered, propagating in the opposite direction of the pulsed light, and it is used for sensing purposes. Three types of light scattering happen in an optical fiber: Rayleigh, Brillouin, and Raman scattering (Fig. 1). Raman and Brillouin scattering have found great acceptance as sensing methods for distributed sensors. Both are based on the difference between the optical properties of the pulsed light and the back-scattered light. Compared to the incident light frequency, ν, the Raman scattering light is shifted ±10–13 THz, whereas Brillouin scattering frequency varies by ±10–13 GHz [21]. The intensity of Raman scattering light is sensitive to temperature changes (ΔT), making it a reliable and widely used temperature sensing system.

Using a Raman system with multi-mode fibers, a resolution of 0.1 °C for ΔT and a spatial resolution of 1 m over a 8 km length is feasible [22]. However, since Brillouin scattering is based on frequency modulation, it is more accurate and stable for long-term use compared to intensity-based Raman techniques [23].

In Brillouin scattering, the scattered light reaches a peak over its spectrum at a frequency shifted from the pulsed light computed by Eq. (1), known as the Brillouin frequency shift, ν_B.

$$\nu_B = 2nV_a/\lambda_o \tag{1}$$

Here, n is the effective refractive index of the fiber, V_a is the acoustic wave velocity of the fiber core, and λ_o is the vacuum wavelength of the incident light. V_a is dependent on temperature and density changes due to strain along the sensing fiber, as is the Brillouin frequency shift, given by Eq. (2).

$$\nu_B = \nu_{B0} + C_\varepsilon \Delta\varepsilon + C_T \Delta T \tag{2}$$

The Brillouin frequency at the initial reading at a given (T, ε) condition is ν_{B0}, and $\Delta\varepsilon$ and ΔT are the strain and temperature changes at subsequent measurements.

Brillouin scattering sensing is particularly useful for strain measurements as it can provide spatial resolution of about a meter along a 50 km long fiber [24]. Measurement resolution can reach 1 °C for ΔT and 2×10^{-5} for $\Delta\varepsilon$ sensing [4].

Among available Brillouin sensing technologies, two types are more common; the first, based on spontaneous scattering, is called Brillouin Time Domain Reflectometry (BOTDR), the other is called Brillouin Time Domain Analysis (BOTDA). BOTDR requires access to one end of the sensing cable, whereas the stimulated scattering system BODTA requires access to both ends of the sensing cable [21].

In stimulated scattering, BOTDA, a weak continuous wave light called the probe beam is back propagated into one end of the fiber while an intense pumped pulse is simultaneously sent into the other end. The stimulation process, i.e. gain, becomes maximized when the frequency