Frequency domain-based distributed and dynamic optical fiber sensing in geotechnical and industrial monitoring

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ABSTRACT: This article reports on recent advancements in the field of distributed optical fiber sensing with a focus on the monitoring of geotechnical structures and buildings. While the classical time-domain approach to distributed sensing is widely known, this article provides an introduction into the frequency-domain analysis technique for both distributed Brillouin measurements (as commonly used for strain and temperature monitoring) and for linear backscattering measurements. The article also addresses an issue which arises when truly distributed measurements are compared among each other; a new approach to calculate differential curves from a measurement and a base-line which avoids misleading large amplitudes at physical events with strong gradients is proposed. Finally, a field test of a new read-out technology, the OFDR (optical frequency domain reflectometry) technique providing dynamic readings of length changes between discrete fiber positions, is presented.

1 INTRODUCTION

For long-range measurements in geotechnical and industrial applications, distributed optical fiber sensors have become a tool of increasing importance throughout the past decade (Glisic and Inaudi, 2007). Classic deformation monitoring (performed by strain gauges etc.) and temperature monitoring (Pt100 and alike) deliver data from fixed, single spots of a structure; quasi-distributed measurements (fiber Bragg gratings) provide a chain of discrete measurement points. In contrast, an optical fiber connected to a device for distributed strain and temperature sensing (DTSS) will provide a continuous profile of strain and temperature – spatially resolved down to less than 1 m – over a range of several tens of kilometers.

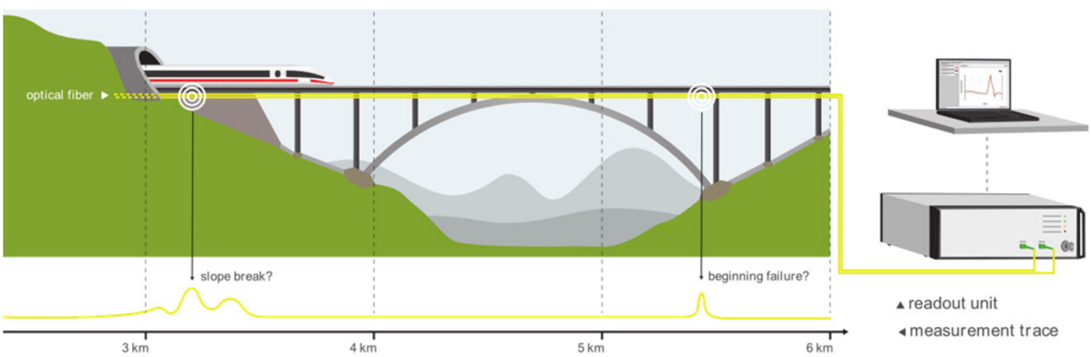


Figure 1: Distributed strain measurements for structural health monitoring using Brillouin sensing in optical fibers

2 FREQUENCY-DOMAIN FIBER OPTIC SENSING

2.1 The frequency-domain approach

The most common approach to acquire spatially resolved information from an optical fiber is to measure the response of the fiber to an optical pulse that is injected from one end (Figure 2). The pulse runs along the fiber; everywhere it passes by, light is sent back to the injection end where it is measured over time. From this time of flight, a spatial profile of the fiber can be constructed, containing the distribution of the optical process that has generated the backwards-travelling light. This process might be linear scattering and reflections (bearing information on attenuation and reflective events) or nonlinear scattering (bearing information on strain and temperature).

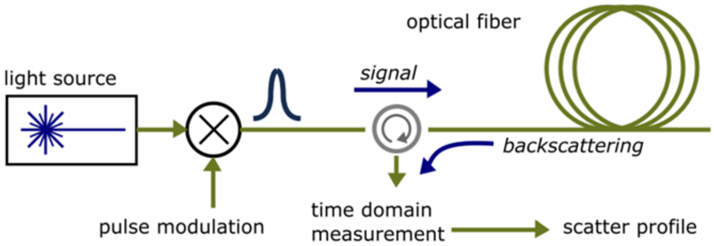


Figure 2: Basic principle of time-domain measurements to record a spatially resolved profile of the backscattering along an optical fiber.

Measurements in the frequency domain provide the same result (a spatially resolved scattering profile of an optical fiber) while avoiding some implementation issues connected to the generation and reception of short optical pulses. Figure 3 shows the concept: Here, the pulses are replaced by sinusoidal waves of a tunable frequency (ca. 5 kHz to 100 MHz). By measuring the system's response to these frequencies (being the spectral components of the optical pulses in a harmonic representation), the transfer function of scattering and reflections along the fiber is recorded. As in a linear, time-invariant system, the pulse response can be entirely constructed from the system's transfer function, a Fourier transform of the measured data will yield the same profile along the fiber that would have been acquired by the use of pulses (Garus, Krebber et al., 1996). The benefit of this approach is the possibility of narrow-band filtering for each component of the pulse and its potential to be integrated into cost-efficient digital hardware.

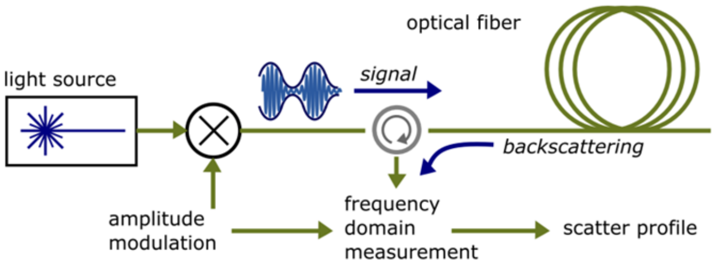


Figure 3: Basic principle of frequency-domain measurements to record a spatially resolved profile of the backscattering along an optical fiber.

2.2 Distributed Brillouin sensing

In DTSS measurements, the nonlinear optical effect of stimulated Brillouin scattering (SBS) is employed: two light waves with a stable, tunable frequency offset are injected into opposite ends of the sensing fiber, where they will form a beat pattern, at which parts of the light will be scattered. By matching the frequency offset of the light waves to the propagation of acoustic fluctuation in the optical fiber, a power transfer from one light wave to the other can be measured; since the acoustic propagation directly shifts with strain and temperature of the fiber, these two quantities can be measured by tuning the light waves' frequency offset (Nikles et al., 1997).

2.3 Quasi-distributed dynamic measurements using the OFDR approach

By means of the Optical Frequency Domain Reflectometry (OFDR) technique the linear backscatter profile of optical fibers can be obtained. In this technique, the complex transfer function of the fiber under test (FUT) in the frequency domain over a wide frequency span is measured and the response in the time domain is calculated by performing its Inverse Fast Fourier Transform (IFFT). An example of this technique was presented (Liehr, Nöther and Krebber, 2010).

In structural health monitoring applications, the OFDR technique can be used as a distributed sensor, recording the linear scattering along optical fibers. It has been shown that especially the use of polymer optical fibers (POF) as sensors yield information on strain spatially resolved within an OFDR measurement trace performing its Inverse Fast Fourier Transform (IFFT). An example of this technique was presented (Liehr, Wendt and Krebber, 2010).

In contrast to such static distributed measurements, the OFDR technique can also be used for highly resolved and fast measurements of the relative position of discrete reflective points along a fiber (Liehr and Krebber, 2012). Such a configuration with a sensing fiber comprising two reflective events is shown in Figure 4.

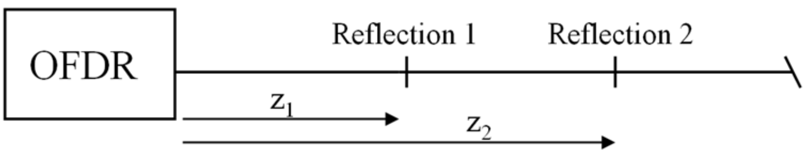


Figure 4: Schematic of the FUT with two reflections at the positions z1 and z2.

Gauge lengths from centimeters to kilometers can easily be implemented. The measurement in the frequency domain allows for precisely extracting location and intensity changes of such reflections from just a few measured frequency points. Measurement can therefore be performed with high repetition rates up to 2 kHz.

A typical measurement of the relative length change between the reflective events is shown in Figure 5: A multi-mode POF was periodically strained and scanned with a measurement repetition rate of 10 Hz.

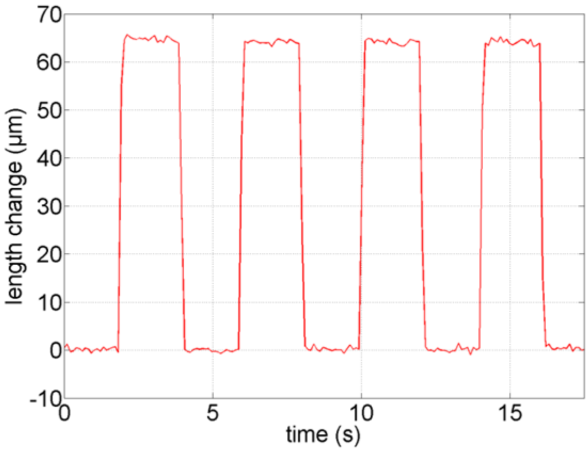


Figure 5: High-resolution measurement of strained multi-mode POF at 10 Hz (Liehr and Krebber, 2012).

In order to obtain a measurement system which can be used outside of laboratory environments, signal generation and reception can be digitally implemented. This is done by integrating a series of elements, such as a Direct Digital Synthesizer (DDS) or Analog-to-Digital and Digital-to-Analog Converters, on a compact board which functions as an interface between the FUT and the signal processing software. Measurements covering a frequency bandwidth of 100 MHz have already been performed, and the expectation is to be able to go up to 500 MHz, which would allow for improved spatial resolution; the digital implementation also provides the perspective to significantly increase the repetition rate of the dynamic measurements.

Application examples of this sensing technique for length change measurements during earthquake tests are presented in section 3.2.

3 APPLICATION AND VALIDATION

3.1 Differential display of distributed measurements

As described in section 2.2, fiber-optic distributed measurements provide uninterrupted readings of a physical quantity (being strain and temperature in the case of Brillouin sensing) along a sensing fiber. From the definition of distributed sensing (Glisic and Inaudi, 2007), a data point in the measurement trace represents the integral value of the measurand along a sensor section of a length equaling the measurement's spatial sampling rate. This is in contrast to point-wise or quasi-distributed measurements, where each reading point represents one fixed sensor at a fixed location, independently from any adjacent sensor in the chain.

Note that the measurement's spatial sampling rate is not necessarily the same as the measurement's spatial resolution: The latter denotes the shortest physical event (like a strained fiber section) that can be accurately resolved, and is governed by physical properties of the optical processes and the shape of the optical signal scanning the fiber. The spatial sampling rate (or "distance resolution") is the distance between two data points which can be increased by oversampling and interpolation of the received signals (see Figure 6).

The fact that a single readout point of a distributed measurement contains the integral information of a stretched-out fiber section provides the advantage of truly uninterrupted detection of critical events; however, there are some implications of this mechanism that need to be accounted for when analyzing distributed measurements.

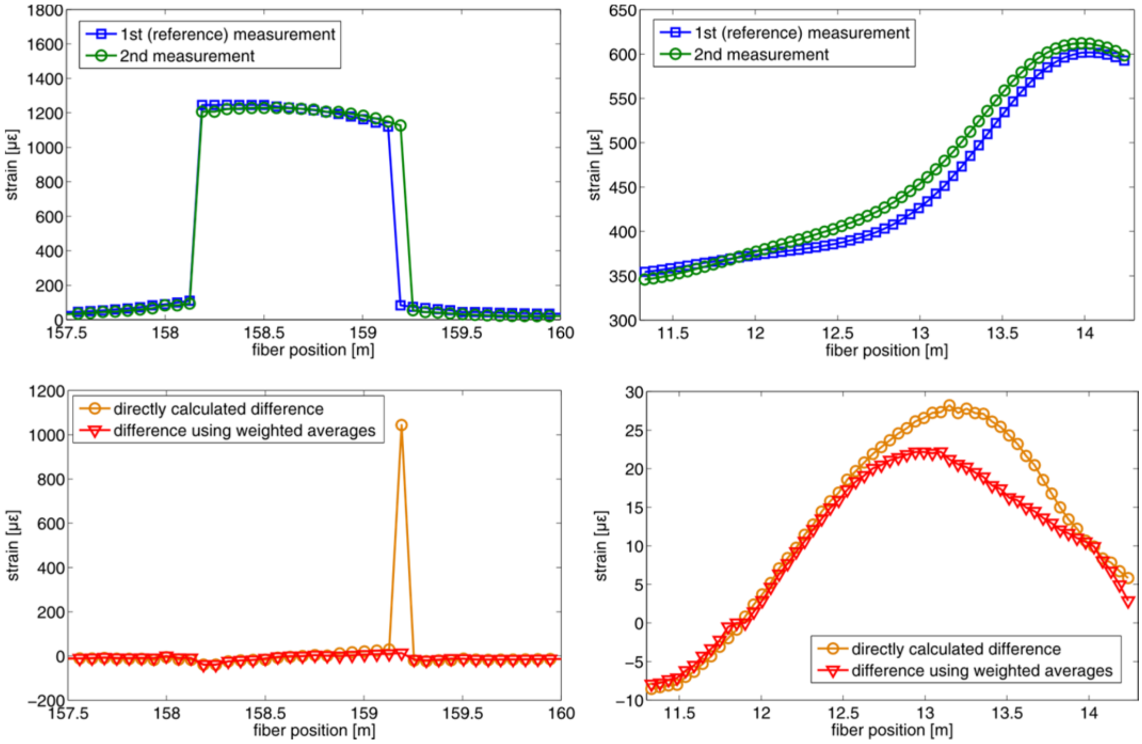


Figure 6: Distributed Brillouin measurements with a 1 m spatial resolution and a spatial sampling rate of approx. 6 cm.

When plotting differential curves – for instance, in order to observe changes along a structure relative to a reference or baseline measurement – the straight-forward approach is a point-wise subtraction of one curve from the other. Figure 6 shows an undesired effect of this operation: The upper graphs show typical distributed strain measurements with a spatial resolution of 1 m and a spatial sampling rate of approx. 6 cm. On the left side, a strained section of 1 m length with abrupt edges is shown; on the right side, a gradual increase in strain is resolved. The curves with circle markers in the lower figures show the point-wise subtraction. The problem becomes evident: Strong amplitudes in the differential curve do not necessarily correspond to what a reasonable observer would interpret from a look at the original curves. The spike in the lower left graph is generated by a slight shift of one of the edges of the strained section. Provided that each data point accounts for the surrounding interval, the decision whether a single point at the precise position of the (physical) edge is determined to lie before or after the edge can be subject to smallest fluctuations in the signal – resulting in spikes in the differential curve that clearly have no physical relevance.

A similar effect can be observed in the gradient in the upper right graph: Again, the amplitude of the differential signal does not represent what a reasonable observer would see as the major event (the increase at 14 m), but by the steepness of the slope (12.5 m to 13.5 m).

While an expert to distributed sensing might be able to account for such effects when observing the differential curve, it is difficult to communicate them to real-life end users in structural health monitoring – and it is even more difficult to define automatic alarm thresholds on the base of such a point-wise differential curve. Therefore, we propose a simple method for the generation of a "smart" differential curve: For each point at a position z_0 in the new measurement, not only the corresponding data point at z_0 in the reference curve (and their difference Δ_1) is taken into account. Instead, the two adjacent data points at $z_0 - dz$ and $z_0 + dz$ in the reference curve are looked at; the one with the smaller amplitude difference Δ_2 to the data point in the new measurements is used to construct a triangle (see Figure 7). By weighing Δ_1 and Δ_2 inversely, a new difference value can be created that accounts for the presence of a sharp edge or a gradient in the neighborhood of z_0 – while avoiding the effect of large amplitudes due to single-point shifts of a detected event.

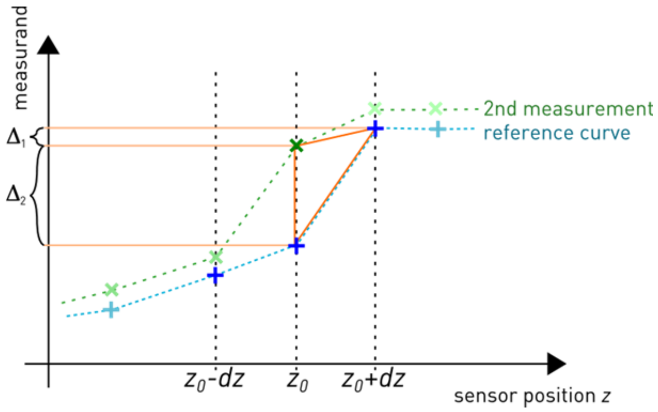


Figure 7: The starting points for the calculation of a difference curve using weighted averages.

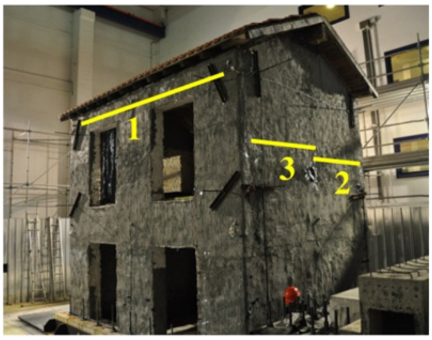
This approach basically follows the same concept of a reasonable observer, who would do his interpretation of the data not by comparing (vertically corresponding) data points of the two measurements point-to-point, but rather by visually comparing the relative positions of the edges or the gradients of events that have been correctly resolved in the original measurements.

The triangular-marked curves in the lower graphs of Figure 6 show the results of the approach: The spike in the left graph is replaced by a small amplitude at the position of the edge. Note that this is no simple (brutal) erasure of the spike; as soon as the edge of the second measurement is shifted by more than one single data point from the reference curve, the technique will see it as a physical event instead of the said effect of distributed measurements and thus indicate it by a strong amplitude in the differential curve.

The gradient in the right graph (again processed with the weighted averages technique) shows a clear shift of its centroid towards the top of the event. It is obvious that the original information – the detection of the event – remains present, while leading the attention of the observer (human or automatic) towards the region of physical significance.

3.2 Seismic shaking table tests using the dynamic OFDR

Within the European project Polytect and the "Seismic Engineering Research Infrastructures for European Synergies (SERIES)" project, the OFDR measurement setup was tested under field test conditions at the facilities of the EUCENTRE in Pavia, Italy. A two-storey masonry building placed on a seismic shaking table has been retrofitted with strengthening technical textiles to undergo vibration testing. We also installed 3 sensor sections on selected locations of the building by simply gluing and screwing the sensor sections in pre-strained condition to the locations of interest. Two different fiber types, 50 µm multi-mode core diameter silica fibers and a POF cable have been installed and were interrogated in parallel as part of the same sensor network. Figure 8 shows the building with indication of the locations of the single sensor sections.



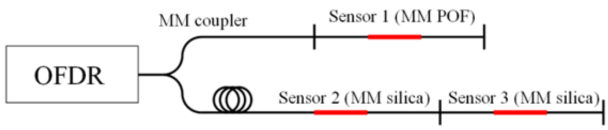


Figure 8: *Left:* Masonry building with indications of the locations of the installed sensors 1 (POF) and sensor 2 and 3 (silica fibers). *Right:* Schematic of the installed fibers and sensor sections with 4 reflection points in the fiber (Liehr and Krebber, 2012).

To protect the silica fiber sensor from damage due to expected cracks in the walls, the sensor fibers have been bonded only at few spots every 50 cm. The sensor application approach for crack detection and crack propagation measurement using brittle silica fibers would have to be some sort of suspended fiber section in pre-strained condition to prevent extreme local strain and fiber breakage. The ruggedness and high strainability of the POF however, would allow direct bonding of the fibers onto the wall with little risk of sensor damage due to cracks. The low Young's modulus of the POF cable ensures a direct strain transfer from the wall to the fiber core. After installation of the sensor fibers, the building was subjected to 5 independent seismic load patterns of increasing acceleration, each lasting about 45 seconds. The seismic acceleration has been applied in direction of sensor 1 and perpendicular to the wall with the sensors 2 and 3.

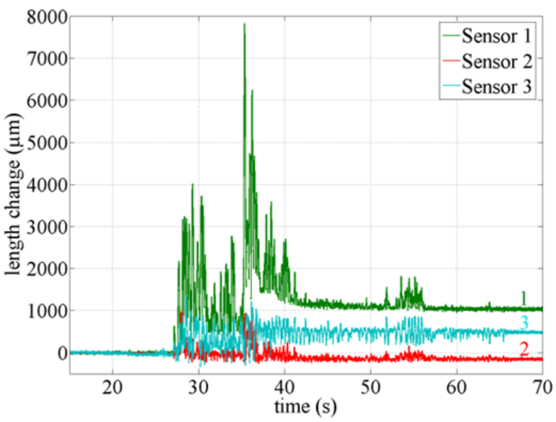


Figure 9: Length change results of all sensor fibers during the seismic load at 160 Hz measurement repetition rate (Liehr and Krebber, 2012).

During the first few tests, several damages have already been detected. Small cracks appeared along sensor 1 and a small crack has been detected by sensor 3. The reading of length change results of the 3 sensor sections during the last seismic shaking test has been conducted with 160 Hz.

Figure 9 shows that the greatest deformation occurred along sensor 1 with a maximum elongation of about 8 mm. It can also be seen that already existing or new cracks caused a permanent deformation of about 1 mm. The acceleration perpendicular to sensor 2 and 3 excites an oscillation of the wall resulting in a concentrated deformation at the location of the existing crack bridging sensor 3.

The measurement showed good correspondence to results obtained with other sensor techniques at similar locations and proved that the proposed technique can be transferred from the laboratory stage towards application-like conditions.

4 CONCLUSIONS AND OUTLOOK

Advancements in the analysis of distributed sensing data have been presented; a new technique for distributed measurements of linear backscattering, suited for fast (dynamic) tracking of the length change between discrete reflective events along a sensing fiber has been introduced along with results from a relevant test setup. In order to pursue these promising approaches, the gained results will be adapted to field-applicable integrated solutions, in which both the digital approach to the frequency domain analysis and the weighted averages technique for differential data display will further be evaluated and validated.

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