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Quasi-distributed displacement sensor for structural monitoring using a commercial OTDR

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Abstract

A quasi-distributed displacement sensor for structural monitoring using an optical time domain reflectometer is demonstrated. Four displacement sensing heads are placed along a standard single mode optical fibre in several locations with different intervals. Their configurations introduce power loss through the decrease of their fibre loop radius when displacement is applied. The decrease of the light intensity with displacement variation is reported. Losses of 9 dB for a ~120 mm displacement with a sensitivity of ~0.027 dB/mm are reported. The quasi-distributed configuration is able to address sensors with ~1 m distance resolution between them.

Keywords: Optical fibre sensors; Displacement sensing heads; OTDR; Quasi-distributed sensor

1. Introduction

Aged civil engineering infrastructures can present high risks if the localised cracks or ruptures are not detected. Therefore, the monitoring and damage detection of

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localised cracks or ruptures in these structures has become important and relevant [1]. Several parameters such as pressure, load, displacement, tension, force, vibration, strain and temperature interact constantly in the structures and the evaluation of their conditions is very important. In this way, many types of optical fibre sensors have been proposed and developed [2]. Due to their properties of electromagnetic immunity and their ability to provide distributed information, this technology has been growing, avoiding serious accidents and guaranteeing a higher level of safety [3].

Optical fibre intensity sensors based on bend mechanisms have been extensively used with various configurations [4–6]. They are simple, reliable, low-cost, can be multiplexed and used in distributed applications. To interrogate this kind of sensors, the optical time domain reflectometer (OTDR) has become a valuable instrument to measure the induced change in the optical intensity at different locations on the fibre [7]. By detecting the loss of the Rayleigh backscattering light, parameters like strain and displacement can be measured. For instance, when the sensing head is stretched and/or compressed, it induces bends in the optical fibres [8,9]. In other cases, the combination of the OTDR with standard microbend sensing heads permits the detection of bend and vibration on large mechanical structures [10,11]. Moreover, sensing configurations using an OTDR have also been developed to measure tensile/compressive strain and to study the loss sensitivity of singlemode and multimode fibres [12].

In this paper, we present a quasi-distributed displacement-sensing configuration comprehending four optical fibre sensing heads based on a bend mechanism induced by displacement. The interrogation system utilises a commercial OTDR, allowing a real-time monitoring. The experimental setup and the measurements are presented and the quasi-distributed sensing configuration is characterised.

2. Sensor design and experimental setup

The sensing head mechanism consists of a fibre tied in the shape of an eight number figure, which was first presented by Sienkiewicz et al. [13]. In that work, a multimode optical fibre (LNF, 62.5/125 μm) was used. In our case, we adopted a singlemode optical fibre (SMF 28, 8.3/125 μm).

Fig. 1 illustrates the sensing head mechanism. When a displacement in the d length occurs, the sensing head size s decreases and power loss is induced through the decrease of the loop radius. The sensor does not require an external mechanism to increase or decrease the bend radius.

To implement a quasi-distributed sensor, four displacement sensing heads were constructed in a continuous optical fibre. The experimental setup was mounted as shown in Fig. 2. It comprehended a commercial OTDR (YOKOGAWA-AQ7260), with loss measurement accuracy of $\pm$ 0.05 dB/dB and a minimum distance sampling resolution of 50 mm, which was connected to a personal computer (PC) for data display, processing and storage. The OTDR locates the position of each sensing head and measures the induced displacement loss through the Rayleigh backscatter light

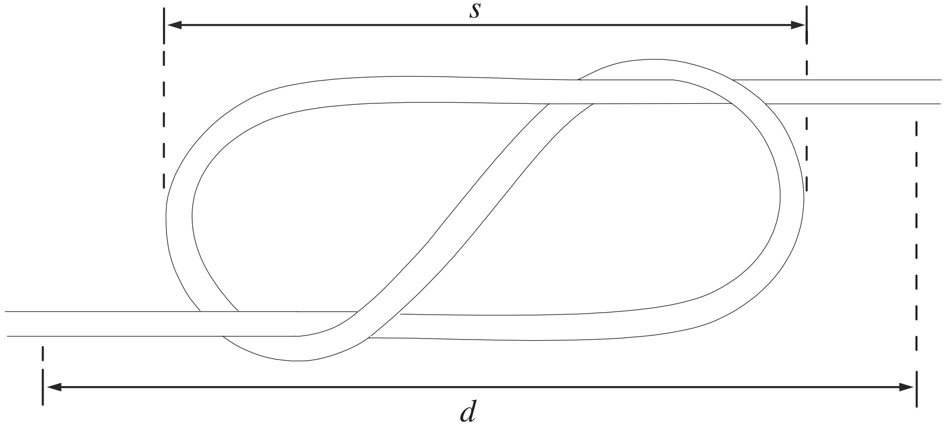


Fig. 1. Sensing head mechanism.

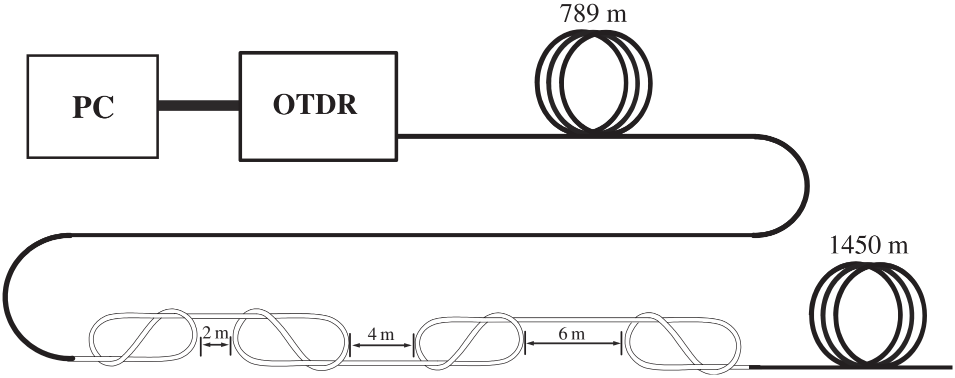
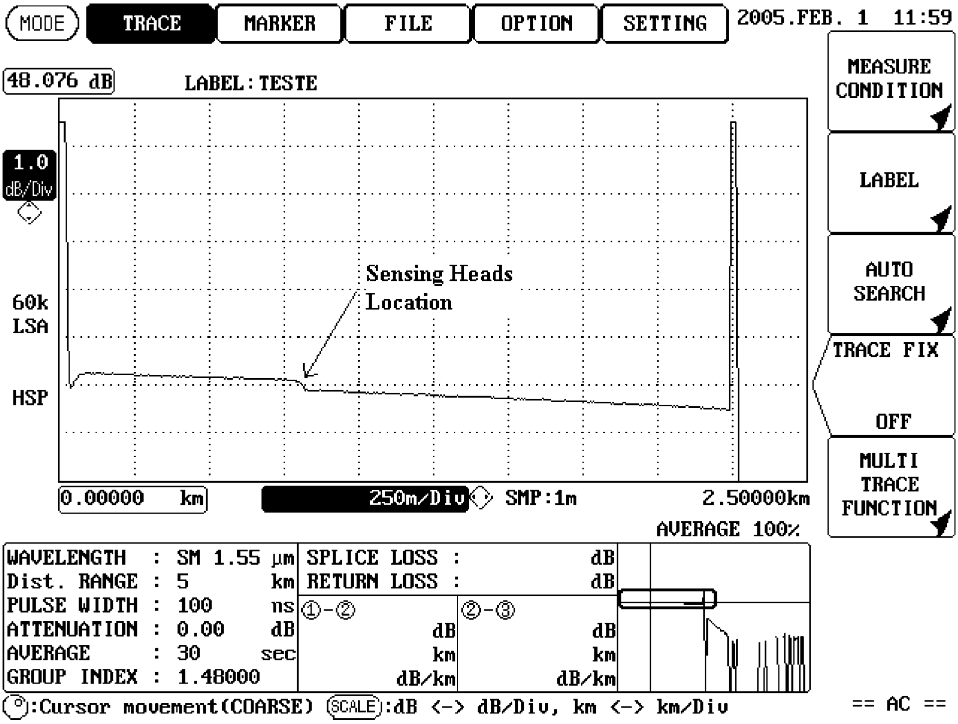


Fig. 2. Experimental setup.

signal. The sensing heads were placed in different intervals between two fibre rolls, of 789 and 1450 m. The first sensing head was positioned at 790 m, the second at 792 m, the third at 796 m and the last at 802 m, resulting in a separation length between them of 2, 4 and 6 meters, respectively. In Fig. 3, we can see the OTDR signal of the entire fibre length showing the position of the four sensing heads.

3. Experimental results

To investigate and characterise the sensing head configuration, measurements were taken selecting the OTDR a light wavelength of 1550 nm and a pulse width of 50 ns. The experiments demonstrated that the losses begin to appear for $s = 75$ mm and were extremely high when reducing s more than 30 mm. In this way, the initial dimension adopted for the sensing head size (s) was 75 mm corresponding to an



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WAVELENGTH   : SM 1.55 µm   SPLICE LOSS  :        dB
Dist. RANGE  : 5      km    RETURN LOSS  :        dB
PULSE WIDTH  : 100    ns    ①-②           ②-③
ATTENUATION  : 0.00   dB            dB            dB
AVERAGE      : 30     sec           km            km
GROUP INDEX  : 1.48000           dB/km         dB/km
:Cursor movement(COARSE) SCALE:dB <-> dB/Div, km <-> km/Div
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Fig. 3. OTDR signal of the entire fibre length.

initial length (d_0) of 125 mm. The displacement (D) was defined as $D = d_{\text{actual}} - d_0$, where d_{actual} is the actual d length. To introduce short displacements, the fibre was bonded on one side of the loop. The increasing of d length decreases the s dimension.

Fig. 4 presents the linear relationship between the sensing head size s and the displacement D. It is important to refer that the maximum displacement D is approximately 180 mm, which corresponds to the breakage of the optical fibre. The ~120 mm displacement D value (30 mm in sensing head size s) corresponds to the maximum applied displacement to each sensing head in our quasi-distributed sensor configuration. For larger displacements the signal collected by the OTDR is too weak to be processed.

As previously mentioned, the increase of D will induce losses through the decrease of the loop radius. In fact, the study of these losses gives the response of each sensing head as a function of the displacement. In Fig. 5, we can see the sensor dynamic range when different displacements were induced. Initially, for a 0–40 mm displacement, the sensing head does not present any significant losses. This is due to the fact the loop radius is not small enough to create the bend effect. The losses only begin to be significant for a displacement D larger than 40 mm. In this case, the sensing head presents an exponential behaviour, reaching a loss of 9 dB for a ~120 mm displacement, corresponding to 0.7 mm of radius curvature. Applying a

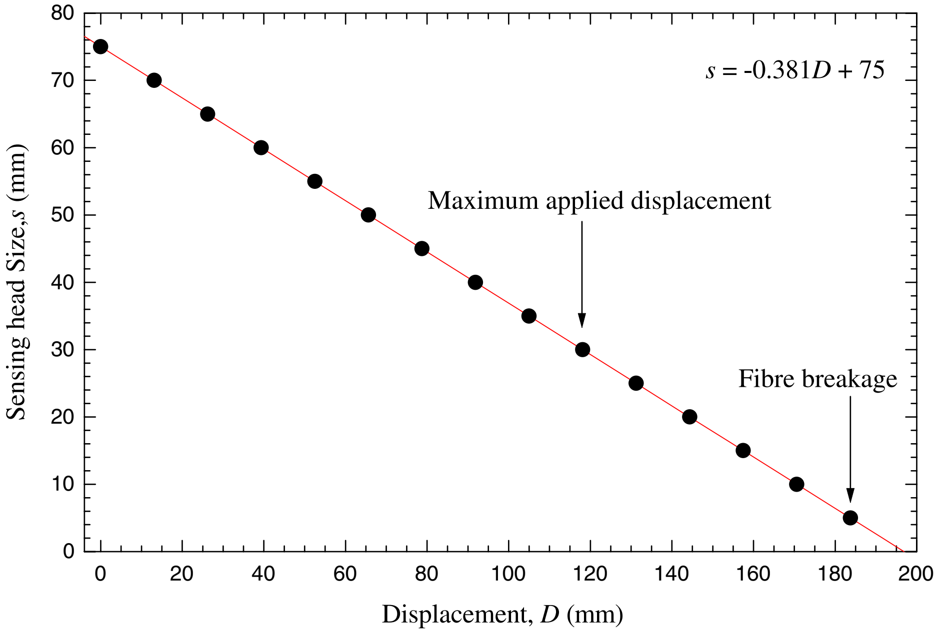

Fig. 4. Relationship between sensing head size s and displacement D.

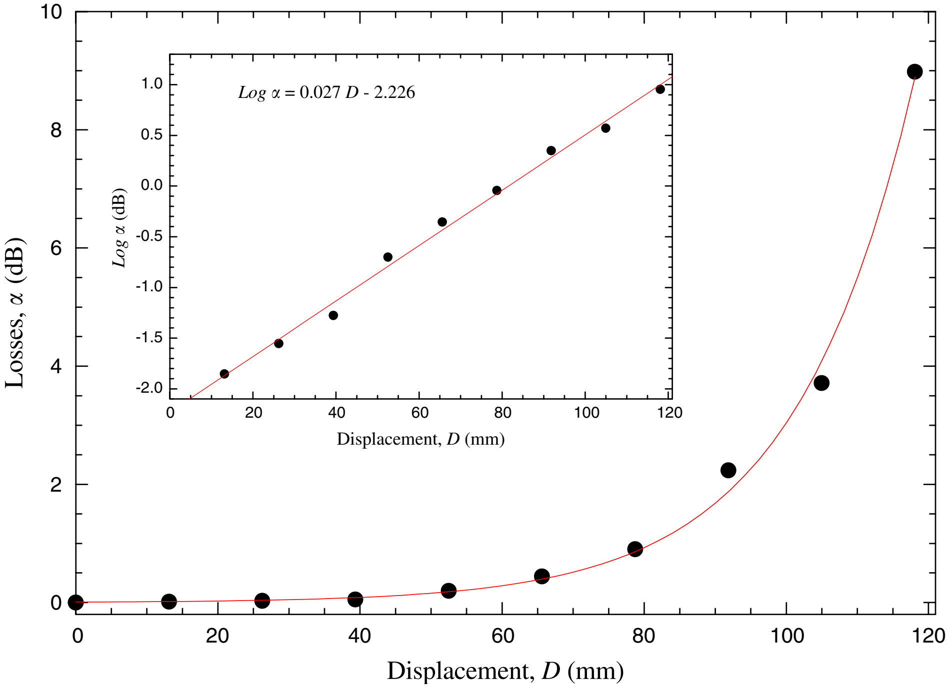

Fig. 5. Experimental results of induced losses with displacement for one sensing head.

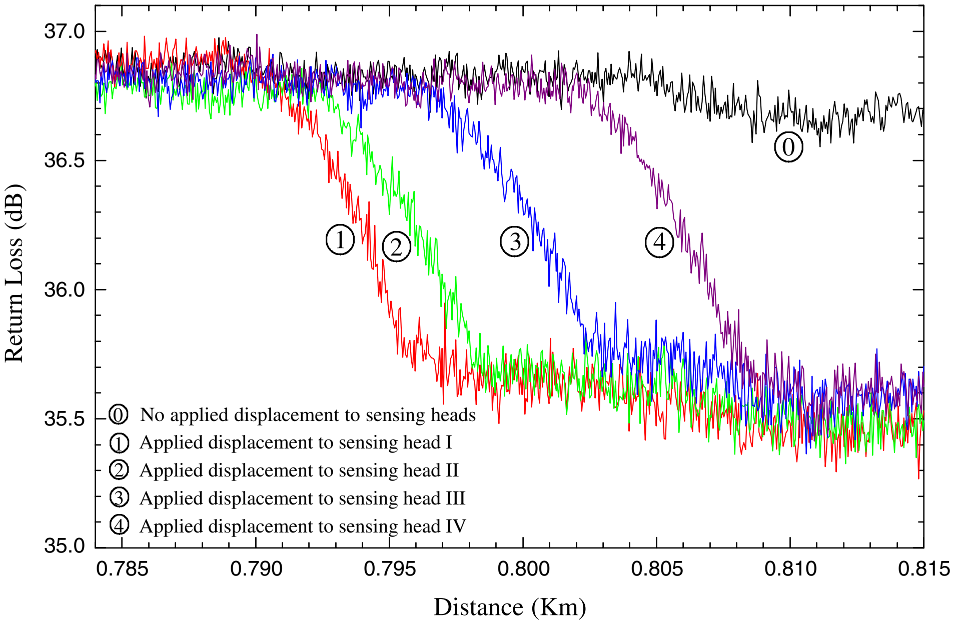

Fig. 6. Experimental results of return loss with distance when a displacement of 80 mm is applied to each sensing head.

logarithm equation on these results, a linear relationship between losses and the displacement, is obtained as it can be seen in the inset of Fig. 5. Moreover, the sensitivity of sensing head was found to be ~0.027 dB/mm, which corresponds to an rms deviation of ±0.98 mm. However, using an appropriate signal processing, the displacement resolution of each sensing head can be optimised.

To characterise the quasi-distributed displacement sensor configuration, we conducted OTDR tests to the four sensing heads that were placed on the optical fibre with the previously mentioned separation length (2, 4 and 6 meters, respectively). Using setup of Fig. 2, a displacement of 80 mm was successively applied on each sensor. The loss for each sensing head was measured when no displacement was applied to the others. Fig. 6 presents the return loss results with distance, detected via the OTDR, for the four displacement sensing heads. As we can see, the OTDR results reveal attenuation change when maximum displacement is applied sequentially to each sensing head. The beginning of the attenuation step corresponds to the sensors locations. For all sensors, a value of ~1.35 dB for the 80 mm displacement was detected. Also, we can see, the measured distance between sensors corresponds to the indicated separation length. Considering the results, the smallest separation length between sensing heads, capable of being detected, is about 1 m.

In order to discriminate the measurements between sensing heads in the quasi-distributed sensor configuration, another experiment was carried out. It consisted of measuring the return loss induced by combining first, two sensing heads and finally,

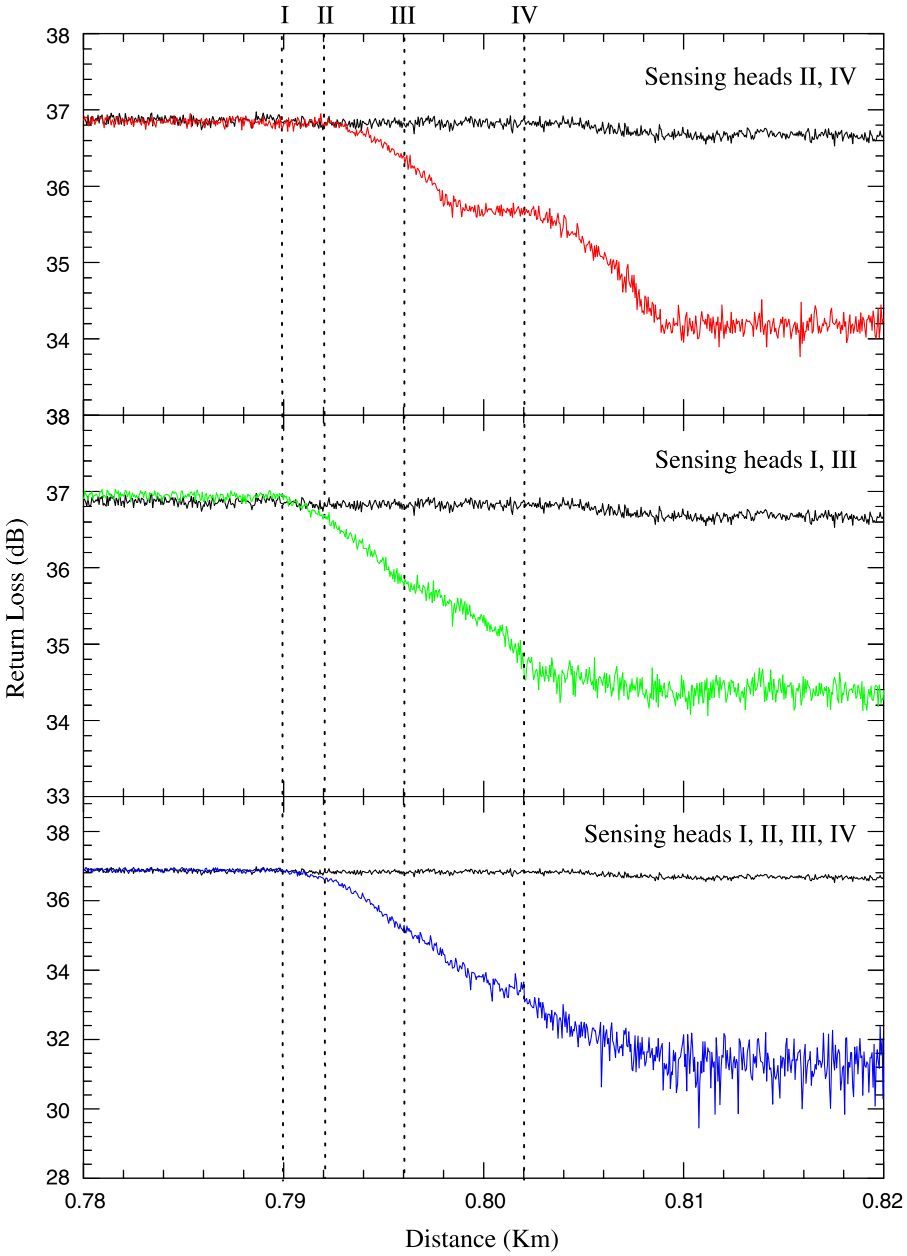

Fig. 7. Experimental results of return loss with distance when combining two or four sensing heads.

four sensing heads. Fig. 7 shows such result when an 80 mm displacement is applied to each sensing head. As it can be seen, when the displacement was applied on sensing heads II and IV, a loss of ~2.70 dB was measured. In the same way, a loss of

~2.70 dB was found for sensing heads I and III, when they are placed in different locations. Finally, we applied 80 mm displacement on the four sensing heads. A loss of ~5.40 dB was found. The vertical dot lines correspond to the beginning of the attenuation step at the location of the sensing heads. Moreover, the combined loss of the four sensing heads correspond to the addition loss found for each single sensing head, ~1.35 dB (Fig. 6).

4. Conclusion

In this paper, we presented a quasi-distributed displacement sensor configuration based on a bend mechanism for the sensing heads, which uses a commercial OTDR capable of addressing sensing heads with ~1 m distance resolution between them. We used four displacement sensing heads, in different positions, with a displacement measurement range of ~120 mm.

The quasi-distributed sensing configuration demonstrated its capability of discriminating the four displacement sensing heads. Although we used four-displacement sensing heads, this interrogation system allows a higher number of sensing heads. This sensing configuration can be embedded in engineering structures for real-time monitoring.

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