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Fiber Optic Sensors and Sensor Networks Using a Time-domain Sensing Scheme

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ABSTRACT

Fiber loop ringdown (FLRD) has demonstrated to be capable of sensing various quantities, such as chemical species, pressure, refractive index, strain, temperature, etc.; and it has high potential for the development of a sensor network. In the present work, we describe design and development of three different types of FLRD sensors for water, cracks, and temperature sensing in concrete structures. All of the three aforementioned sensors were indigenously developed very recently in our laboratory and their capabilities of detecting the respective quantities were demonstrated. Later, all of the sensors were installed in a test grout cube for real-time monitoring. This work presents the results obtained in the laboratory-based experiments as well as the results from the real-time monitoring process in the test cube.

Keywords: Fiber Loop Ringdown; Structural Health Monitoring; Water, Crack, and Temperature Sensing; Sensor Network

1. Introduction

Fiber loop ringdown (FLRD) is a time domain sensing technique which utilizes the rate of the decay of a light pulse trapped inside a closed fiber loop to generate its sensing signal—"*ringdown time*". FLRD can detect various chemical and physical quantities, such as small volume of liquids, pressure, temperature, refractive index (RI), etc [1]. The trapped light pulse traverses inside the fiber loop many times before it dies out completely and in each round trip a small amount of the light is transmitted out of the loop to a detector. The temporal profile of the transmitted part follows a single exponential decay. The *ringdown time* is obtained from this exponential decay waveform of the transmitted light intensity. Owing to different optical losses inside the cavity, the ringdown time changes. If an optical loss occurred inside the fiber loop can be related to an event, for example a change in pressure, temperature, stress, strain, *etc*., or even a change in RI around the fiber core, then that particular event can be sensed by observing a change in the ringdown time. Details about the FLRD sensing technique and its various applications, such as sensing physical parameters, chemical species, biological quantities, etc., can be seen in a number of publications [2-9]. However, it is a very recent progress, in which FLRD-based sensors have been developed and demonstrated for water, crack and temperature sensing in actual concrete structures with possibility of sensor networking, an important requirement in structural health monitoring (SHM) [10, 11]. In this paper, we describe the design and development of three FLRD sensors, namely, FLRD water, crack, and temperature sensors developed in our laboratory, and discuss the results obtained from the experiments conducted in laboratory conditions and from the real-time monitoring process in the concrete structures.

2. Experimental Set-up

Figure 1 shows schematic of a typical FLRD sensor and its configuration. The figure depicts how all of the three types of sensors, *i.e.* water sensors, crack sensors, and temperature sensors, were connected to a fiber loop. The part marked as *A*, *B*, or *C* in the figure represents three different sensor heads for the three different sensing functions. The sensors were controlled by the electronics, depicted in the upper part of **Figure 1**, named as the sensor control system. In this particular experiment, a single mode fiber (SMF) (Corning Inc.) was used to construct a fiber loop of 120-m long, as shown in the figure. A diode laser (NTT Electronics) operating at 1550 nm was used to obtain laser pulses which were injected into the fiber loop through a fiber coupler (Opneti Communication Co) with a coupling ratio of 0.1/99.9. The transmitted intensities were collected using a photodiode detector (Thorlabs Inc.). The ringdown signals were monitored by an oscil-

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loscope; subsequently, changes in ringdown time were recorded by a computer. A brief discussion on the instrumentation process of the three sensors is described in their respective sections later.

3. Results and Discussion

The first-hand experiments with all three sensors were conducted in our laboratory. Subsequently, all of the three types of sensors were deployed in a test grout cube with dimensions of 10 ft × 10 ft × 8 ft, in the designated test site of the US Department of Energy, located in Miami, Florida, for real-time monitoring. First, the sensors were installed in an installation panel and the panel was then loaded inside the test cube that later was entombed by wet grout. Upon drying of the grout, the sensors remain embedded in the grout cube. The extended arms of the fiber cable, from the sensor unit, coming out of the grout cube were connected to the sensor control system in a similar way as shown in **Figure 1**. The sensors were switched alternatively one at a time and the data from all of the sensors were recorded individually, often for a long duration of time, *i.e.* a few hours to a few days.

Some of the results obtained from both the experiments, *i.e.* in the laboratory environment and in the real-time monitoring in the test grout site (Miami, FL), for the three types of the sensors, are presented below.

3.1. Water Sensor

After the plastic jacket of the single mode fiber (SMF) was removed, one section of the fiber was etched in a 48% Hydrofluoric (HF) acid solution for 32 - 33 min to prepare a FLRD water sensor head. Once a water sensor head was created, concrete was prepared by mixing cement-aggregate (Quikrete) and water. After a half of a carton bar, with dimensions of 35 cm × 5 cm × 5 cm, was filled with the concrete, the etched fiber was placed inside the concrete bed and the carton bar were filled completely. It took about two days for the concrete bar to dry out completely. The sensor head remained embedded in the concrete bar, forming one sensor unit. **Figure 2** shows FLRD water sensor's response, for a time duration of 19 hrs, with the experiment conducted under laboratory conditions. After the 1-hr data collection with the dry concrete bar, 10 ml water was poured on the concrete bar surface to test the sensor's response. Whenever the poured water reached the sensor head, the FLRD sensor sensed the water in near-real time, resulting a change in ringdown time. Later, the ringdown time decreased gradually and returned to the baseline when the concrete bar dried out again.

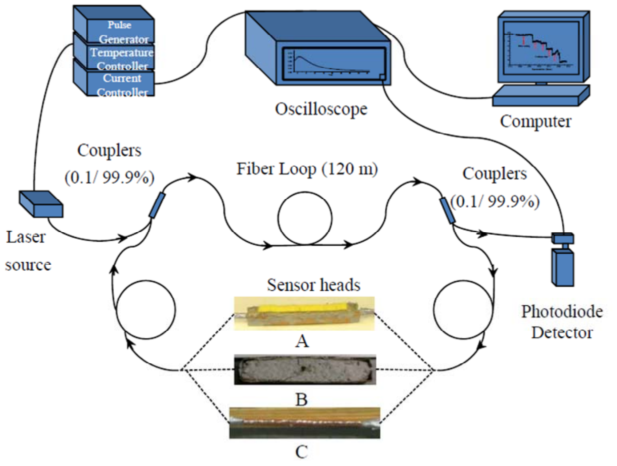

Figure 1. A laboratory-based fiber loop ringdown system. One sensor control system operates multiple FLRD sensor units, *e.g.* sensor units A, B, and C.

Figure 2(b) shows the data collected from the FLRD water sensor after the sensor was embedded into the test grout cube. The data shows the FLRD water sensor's behavior before, during, and after the grouting process. The increase in the ringdown time suggests the presence of water around the sensor head, which dried out in time later, as exhibited by the decrease in the ringdown time.

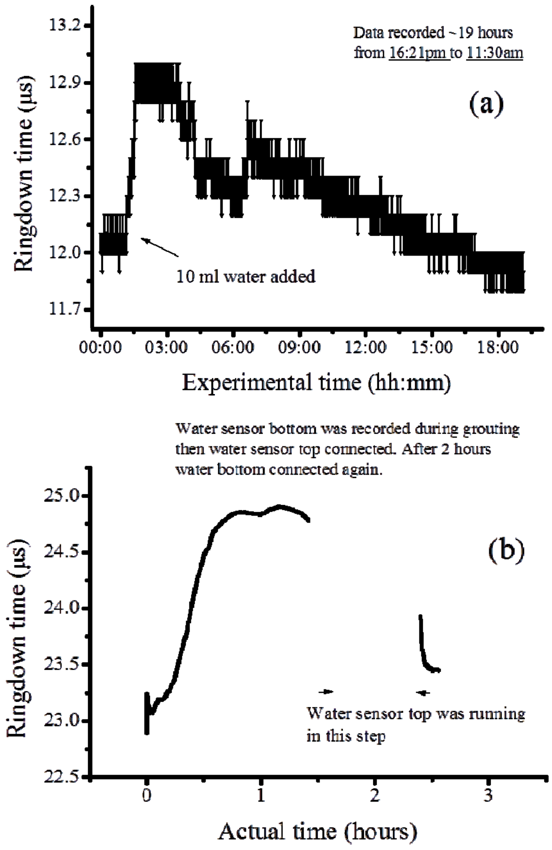

Figure 2. (a) Response of the FLRD water sensor; experiment conducted under laboratory conditions. (b) Data from the FLRD water sensor embedded in the test grout cube that was located in Miami, FL.

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3.2. Crack Sensor

Figure 3(a) shows the results from one of the FLRD crack sensor units, with the experiment conducted in the laboratory environment. A sensor unit, with dimensions of 20 cm × 5 cm × 5 cm was constructed by embedding an optical fiber cable in a concrete bar; while during the process of forming the concrete bar, a bare SMF was laid down as it is, *i.e.* without any modification, inside the concrete bed, along the longest axis of the bar, so that, upon drying it became an integrated unit. The extended fiber cable, *i.e.* the small portion coming out from the two ends of the bar, was spliced into a fiber loop. Cracks were produced manually, by hitting a nail on the top surface of the bar; subsequently, changes in ringdown time were observed. In this particular experiment, from the point of no cracks on the surface to a crack with a surface crack width (SCW) of 3.5 mm wide, measured on the top surface of the bar, a significant change in the ringdown time, *e.g.* from 15.5 µs to 9.5 µs, was recorded. Experimentally, all of the crack sensors responded to a SCW as small as 0.5 mm, which was exhibited by a considerable change in the ringdown time, from 0.5 - 1.0 µs for a 0.5 mm increase in SCW, as shown in **Figure 3(a)**. This result leads to a theoretical SCW detection limit of 31 µm.

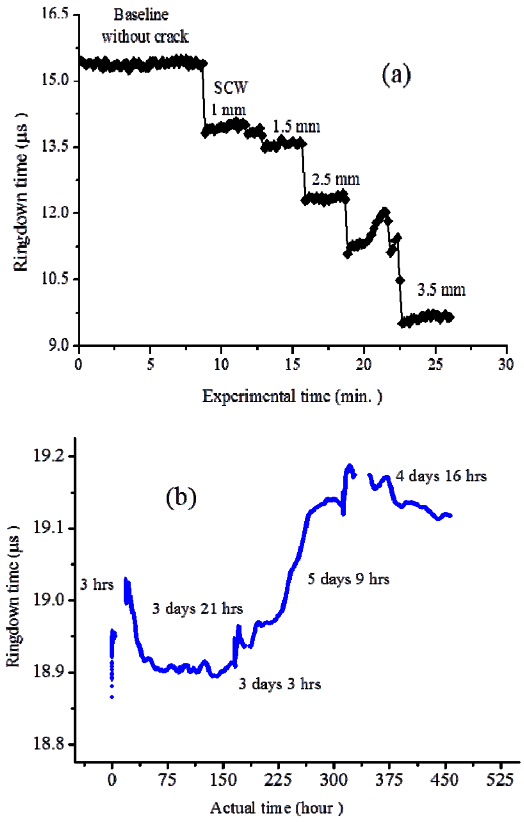

Figure 3. (a) Response of the FLRD crack sensor in the laboratory environment (Starkville, MS). (b) Response of the crack sensor installed in test grout cube in Miami, FL.

Figure 3(b) shows real-time monitoring results from the sensor unit that was installed in the test grout cube. The data were recorded continuously for 20 days, starting from the time when the grouting began. Unlike the laboratory experimental results, *i.e.* in **Figure 3(a)**, the change in ringdown time in this case was not sharp, instead a slow change in the ringdown time was observed. Decrease and increase in the ringdown time indicate a possible contraction(s) and expansion(s) that might have happened in the grout volume in the process of drying of the grout cube.

3.3. Temperature Sensor

FLRD temperature sensors were fabricated by using a commercially available fiber Brag grating (FBG) with a central wavelength at 1567 nm. In the FLRD temperature sensors, the FBG itself acts as a sensor head; therefore, it does not require any modification of the fiber to construct a sensor head. However, the FBG was covered by a copper tubing to protect it from being damaged. Two FLRD temperature sensors were embedded into the grout cube for testing. **Figure 4** shows the remotely collected (in Starkville, MS) data from one of the two FLRD temperature sensors during a period of 12 days.

4. Conclusions

Three types of fiber loop ringdown (FLRD) sensors were designed and developed for the purposes of water, crack, and temperature sensing in concrete structures. The performance of the sensors was first tested with small size concrete bars in our laboratory at Mississippi State University, Starkville, MS. The laboratory experimental results established the idea that FLRD technique was indeed capable of sensing water, cracks, and temperature in actual concrete structures. Later, all of the sensors were

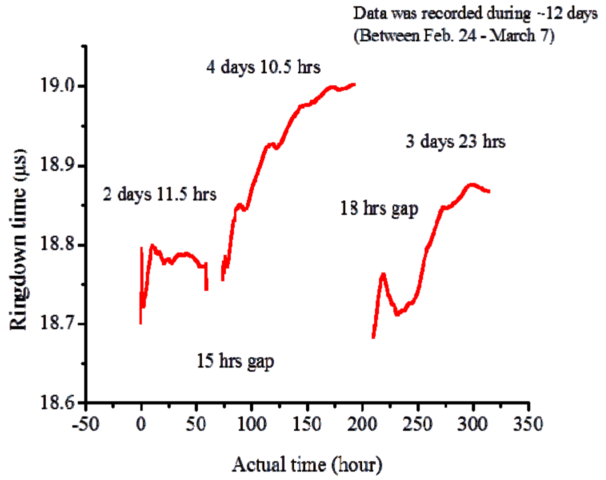

Figure 4. Response of the FLRD temperature sensor for a period of 12 days.

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entombed in the test grout cube, with dimensions of 10 ft × 10 ft × 8 ft, located in Miami, Florida, for evaluating its performance in real-world scenarios. The sensors are controlled and data are still being collected, remotely in our laboratory. The results from both the experiments, i.e. conducted in the laboratory and from the real-time monitoring at the test site, have been discussed in this work. This work represents, for the first time, the study of FLRD technology in real-world applications.

5. Acknowledgements

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