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Concrete temperature monitoring using passive wireless surface acoustic wave sensor system

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ABSTRACT

In this paper, a novel nondestructive method for detecting temperature variations of concrete using a passive wireless surface acoustic wave (SAW) sensor system is described. Performance of the SAW orthogonal frequency coded (OFC) temperature sensors was evaluated in air, liquid, and concrete. To verify the response of the SAW sensor, temperature was also measured using commercially available thermocouples and compared with the extracted temperature in all environmental conditions. Analysis of the measured data showed that the SAW temperature sensor system was successful in detecting temperature over a wide range in all tested conditions with a high degree of accuracy and short interrogation time. When the sensors were embedded within a 2-in. thick concrete cover, the maximum read distance was approximately 4 m.

1. Introduction

Information on the temperature of concrete is significantly important in many areas of civil engineering, especially in the concrete maturity [1–3] and hydration kinetics [4–8]. Maturity is an excellent indicator of in-place strength development and quality from fresh to hardened concrete [9]; therefore, concrete strength is often estimated by measuring its maturity [10]. Curing temperature is one of the parameters considered as a critical factor in the progress of cement hydration by influencing the stability and the transformation of hydrates, and strength development [4,5]. For example, increased curing temperature may improve the strength of concrete at early age [11,12]; whereas, long-term concrete strength can be decreased [3,8]. This is because elevated curing temperature increases the reaction rate [13,14] at early stage of hydration, but also increases the density of hydration products [15], which slows down the hydration process [7].

At elevated temperature, the inhomogenously distributed precipitating hydrates cause coarser porosity within the cement matrix [16] that also influences the composition of the pore solution [8]. Therefore, high temperature development during setting and curing of concrete can cause a number of detrimental effects, not only on the fresh, but also on the hardened properties of concrete, such as increased thermal stresses [17,18] and crack tendency for dry shrinkage [19]. For these reasons, providing a real-time, in-place, direct measurement of concrete temperature is one of the most important challenges in structural health monitoring of civil infrastructures.

Surface acoustic wave (SAW) devices are considered as ideal candidates for structural and material health monitoring applications, because of their reliability and long life [20–23]. In addition, SAW sensors are known to be extremely rugged and can be manufactured in a relatively small size [20,23]. In this paper, a passive wireless SAW temperature sensor was used to monitor the temperature variations of concrete. The results of three experimental investigations are discussed to evaluate the performance of the SAW sensors: (1) commercial thermocouples and the SAW temperature sensor were interrogated in air and in liquid with varying temperature, (2) the SAW sensor and thermocouples were embedded in concrete and interrogated during the initial curing of the concrete and when temperature of the cured concrete was controlled in a temperature chamber, and (3) the SAW sensor extracted temperature precision was determined as a function of read distance when embedded in the cured concrete sample.

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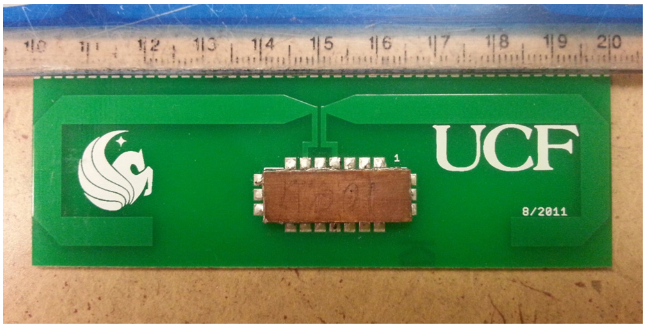

Fig. 1. SAW temperature sensor (packaged center) with folded dipole antenna on a printed circuit board.

2. Passive wireless SAW temperature sensor system

The temperature sensor platform comprises three parts: a passive wireless SAW sensor (Fig. 1), an external transceiver or reader (Fig. 2), and post-processing software for extraction of sensor information. For experiments presented herein, an Agilent E5061B vector network analyzer (VNA) provides the transceiver function, with port 1 as the transmitter function and port 2 as the receiver function. The VNA is a readily available commercial system that provides an excellent method for capture of signal over a wide bandwidth. The VNA was programmed to the desired IF bandwidth and averaging, center frequency and bandwidth, 915 MHz and 100 MHz, respectively. The VNA simulates a synchronous receiver that can sum multiple sweeps for improved SNR. Other previously described transceivers have been specifically designed for given specifications and could be adapted for these measurements also [24]. After wireless sensor interrogation and signal reception, post-processing software extracts the sensor's RFID and embedded temperature information. The combination of the VNA and the software provides a synchronous correlator receiver. Orthogonal frequency coding (OFC) [25–27] is a scheme used to encode the identity of a SAW temperature sensor using both time and frequency domain diversity. The bandwidth and time diversity, using adaptive correlation techniques, provide advantages for pulse compression and increased processing gain [28,29], which increases accuracy and precision over other approaches.

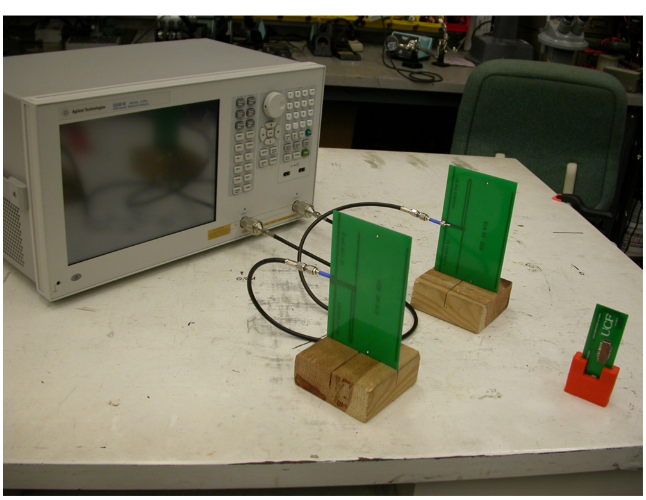

Fig. 2. A commercial vector network analyzer used as a transceiver simulator connected to two printed circuit board (PCB antennas. A single SAW sensor and PCB folded dipole antenna is shown in a plastic (red) holder). The VNA, and computer with appropriate software, simulates a synchronous correlator transceiver. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

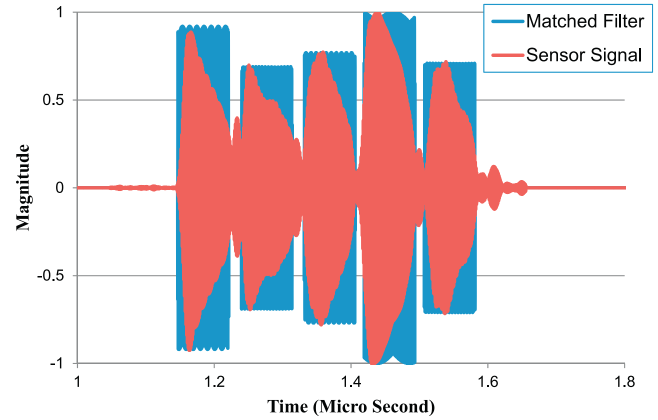

Fig. 3. This plot shows a measured 5-chip, OFC SAW signal time response, marked as *Sensor Signal*. Superimposed is the corresponding ideal, theoretically generated *Matched Filter* time response composed of time truncated sinusoidal functions at the corresponding chip orthogonal frequencies. As temperature changes this complex sensor signal expands or contracts in time and the scaling factor of the matched filter yielding the best correlation between the ideal and measured responses extracts the sensor's temperature.

The 915 MHz SAW sensor is fabricated on a Y-cut Z-propagating Lithium Niobate (YZ $LiNbO_3$) crystal substrate that has a known linear relationship between the rate of change of velocity and temperature, 96 ppm/C, and is used in the temperature extraction process. The SAW device uses standard integrated circuit processing techniques to produce the device structures. The interdigital transducer (IDT) and reflector are fabricated using a lift-off process with aluminum electrodes, yielding minimum feature size of approximately 0.8 μm. The device consists of an IDT with five sets of OFC reflector banks on one side. The crystal die is attached to a package and the IDT is wire bonded to the electrical connections of this package. The package is soldered to an omnidirectional dipole antenna of 2 dBi gain. The wireless interrogation signal received by the antenna attached to the transducer is converted into a mechanical wave, which propagates to the Bragg reflectors and is frequency selectively reflected back to the IDT, where the mechanical wave is converted back into an electrical signal and reradiated by the antenna to the receiver.

An adaptive correlator software routine was developed that enables a real-time measurement of temperature variations using the temperature coefficient of delay (TCD). The temperature is extracted by creating compressed and expanded versions of the sensor's matched filter, based on the known TCD, applied to received sensor time signal as shown in Fig. 3. An optimization process extracts measured time and frequency domain changes that correlates, or maps, to the sensor's temperature changes. The process of temperature extraction is accomplished in real-time, depending on the transceiver system, and required precision and accuracy [30].

3. Experimental procedure

3.1. Response of the sensors in air and liquid

Before embedding the SAW temperature sensor in concrete, the response of the sensor was measured in air and in tap water as a means to verify system functionality in a liquid medium. This provided initial data and insight into the effects of hydration and conductivity on the antenna and the returned signal. As a control, temperature was also measured using a commercially available thermocouple that is connected to an Omega HH309 Data Logger Thermometer. Initially, the SAW sensor and thermocouple were placed in a chamber where temperature was increased from room