Water presence detection in a concrete crack using smart aggregates

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Liquid migrating into existing concrete cracks is a serious problem for the reliability of concrete structures and can sometimes induce full concrete structural failures. In this paper, the authors present recent research on water presence detection in concrete cracks using piezoceramic-based smart aggregate (SA) transducers. The active sensing approach, in which one piezoceramic transducer is used to generate stress waves and others are used to detect the stress wave responses, is adopted in this research. Cracks formed in concrete structures act as stress reliefs, which attenuate the energy of the signals received by the SAs. In case of a crack being filled with liquid, which changes the wave impedance, the piezoceramic transducers will report higher received energy levels. A wavelet packet-based approach is developed to provide calculated energy values of the received signal. These different values can help detect the liquid presence in a concrete crack. A concrete beam specimen with three embedded SAs was fabricated and tested. Experimental results verified that the SA-based active sensing approach can detect a concrete crack and further detect the liquid presence in the concrete crack.

\textbf{Keywords:} water detection; concrete crack; smart aggregate; active sensing; piezoceramic sensors and actuators

1. Introduction

Aging infrastructure all around the world demands significant focus and expenditure. Most aging infrastructure is concrete structure. Health monitoring of concrete structure has been studied for many years. Although the study has been ongoing for many years, the detection of liquid presence in concrete cracks rarely attracts enough attention. However, the detection of liquid presence in concrete cracks is significant for the health of the concrete. It is well known that cracks in concrete structures act as conduits, which could cause liquid migration. In the case of decommissioned nuclear structures, it is of great importance to detect the radioactive liquid leaking through cracks in concrete walls to the ground. Additionally, the detection of liquid presence in concrete cracks is also crucial for concrete dams. If water with particular chemical compositions remains in concrete cracks for a long time, the erosion of the concrete interface and embedded rebar may cause a sustained damage and can even lead to complete structural failure of
the concrete dam. Therefore, the detection of liquid presence in concrete cracks is essential and meaningful to the concrete structures.

Crack detection for concrete structures is one of the most popular topics for concrete health evaluation and has been studied in the recent past two decades. Image-based crack detection is a traditional method for concrete crack monitoring. Ito et al. [1] presented integrated image processing techniques with a high-resolution camera to extract crack regions. Fujita et al. [2] demonstrated two methods of preprocessing in order to eliminate the noise from the crack images. Consequently, Yamaguchi and Hashimoto [3,4] developed a highly accurate and efficient method for concrete crack detection using percolation-image processing. Ultrasonic-based concrete structure health monitoring is also an effective method. Tanaka [5] presented the single and multiple inspections of concrete cracks using ultrasonic sensors. Antonaci et al. [6] described the mechanical characteristics of the concrete with discontinuity surfaces under loads using a nonlinear ultrasonic non-destructive technique. The impedance-based crack detection process is a real-time, qualitative damage detection method [7,8]. The impedance-based approach has been applied to the health monitoring of trusses [9], reinforced concrete bridges [10], reinforced concrete specimens [11,12], reinforced concrete shear walls [13] and composite reinforced concrete/masonry walls [14].

Moisture and water detection in concrete structures is another field that attracted concerns in recent years. Moulton and Toutlemonde [15] presented some quantitative results to describe the moisture transfers in a concrete beam using weighing and gamma densitometry. Yeo et al. [16] and Ho et al. [17] successfully developed Fiber Bragg Grating (FBG) sensors with moisture-sensitive polymer coatings to measure the moisture content of different concrete samples. Ong et al. [18] applied the wireless, passive embedded sensor to monitor the water content in real time. Water in concrete can be detected by analyzing the propagation velocity of ultrasonic waves. The disadvantages of this method are probably the high cost of bulky equipment and lack of robustness.

Although crack and water detection in concrete have been studied for many years, not enough attention is concentrated on the detection of liquid presence in concrete cracks. In this paper, the authors utilize the SA-based active sensing approach to detect water presence in a concrete crack. When a concrete crack is filled with water, the water changes the wave impedance and influences the received signal energy from sensors. Therefore, the water presence in a concrete crack can be detected by comparing the received energy levels before and after the water migrates into the concrete crack.

2. Piezoceramic-based smart aggregate transducer
Piezoelectricity is the major property of piezoceramic materials. When a mechanical stress is applied to such the material, an electric field proportional to the magnitude of the stress is produced. Conversely, when an electric field is applied to the piezoelectric material, a mechanical stress develops and may produce a shape change of the piezoelectric material.

Lead zirconium titanate (PZT) is one of the most commonly used piezoceramic materials. In order to protect the fragile PZT patch, smart aggregate (SA) is designed by sandwiching a waterproof piezoelectric patch with lead wires between two mating marble blocks as shown in Figure 1 [19]. The fabrication of the SA with a BNC connector is shown in Figure 2. The dimension of the PZT patch is 15 mm × 15 mm, and the
thickness is 0.3 mm. The diameter and height of the SA are 25 mm and 20 mm, respectively. Owing to the great stability of physical and chemical properties of marble, distributed SAs functioning as actuators and sensors can be embedded into concrete structures, which can sustainably monitor the health of structures. In recent years, SAs have been deployed for the structural health monitoring of various fields, including early-age concrete hydration monitoring [20,21], soil freeze-thaw monitoring [22], bridge impact detection [23], and concrete crack monitoring [24].

3. Principles

3.1. Active sensing approach

Water detection using an active sensing approach relies on the change of received stress wave energy. Figure 3 is a diagram of stress wave propagation through a crack between SAs. One SA is utilized as an actuator to generate the desired stress waves that propagate in the concrete. The other SA is utilized as a sensor to detect the stress wave response. When a crack occurs in the concrete, the crack functions as a stress relief, which reduces the received stress wave energy. In this case, very little stress wave energy can be detected from the SA sensor.
Subsequently, liquid migrating into the concrete crack changes the wave impedance when a stress wave propagates through the crack. Stress wave energy partly recovers the wave propagation, as shown in Figure 4. The whole process of water presence detection in a concrete crack is presented as the ‘interruption’ of the stress wave transition when cracks form and the ‘recovery’ when water migrates into the concrete crack. Since the wave impedance changes by both crack and water, the energy level of the received stress wave can be utilized to detect the crack and the further water migration in the crack.

3.2. Wavelet packet-based analysis

The collected sensor energy is an important indicator to evaluate the different conditions of crack and water presence in concrete. To quantitatively determine the case when water migrates into a concrete crack, wavelet packet-based analysis is applied to offer the corresponding values of the received energy due to different cases.

The sensor signal $X$ can be decomposed by $n$-level wavelet packet decomposition into $2^n$ signal sets $\{X_1, X_2, \ldots, X_{2^n}\}$. $E_{ij}$ is the energy of the decomposed signal, where $i$ is the time index and $j$ is the frequency band ($j = 1 \ldots 2^n$). $X_j$ can be expressed in Equation (1).

$$X_j = [X_{j,1}, X_{j,2}, \ldots, X_{j,m}]^T$$ (1)

Figure 3. The stress wave propagation through a concrete crack.

Figure 4. The stress wave propagation through water.
where $m$ is the amount of sampling data. Additionally, the energy of the decomposed signal is defined in Equation (2):

$$E_{ij} = |X_j|^2 = x_{j,1}^2 + x_{j,2}^2 + \cdots + x_{j,m}^2$$ (2)

The energy vector of the signal at time index $i$ is defined in Equation (3):

$$E_i = [E_{i,1}, E_{i,2}, \ldots, E_{i,2^n}]$$ (3)

Based on the definition of energy vectors ($E_i$), the total sensor energy associated with time index $i$ can be obtained by the sum of energy vector values. The total sensor energy $E$ is given in Equation (4):

$$E = \sum_{k=1}^{2^n} E_{i,k}$$ (4)

### 3.3. Prior experimental verifications

#### 3.3.1. Water presence detection

In this verification, two SAs were fixed by clips with a 1 mm gap between them, as shown in Figure 5. SA-1 was used as an actuator connected to a function generator (Agilent 33120A) and SA-2 was used as a sensor connected to an oscilloscope (Waverunner LT342). The SA actuator generated a swept sine wave signal via the function generator. The parameters of the swept sine wave are shown in Table 1. In the meanwhile, SA-2 was used to detect the wave response. The amplitude of the wave was recorded by an oscilloscope.

The test was operated in two cases described as follows:

![Test setup: (a) test setup photo; (b) close-up photo of two SAs.](image)

**Figure 5.** Test setup: (a) test setup photo; (b) close-up photo of two SAs.

**Table 1.** Detailed parameters of the swept sine wave signal.

| Parameter          | Value   |
|--------------------|---------|
| Start frequency    | 1 Hz    |
| Stop frequency     | 1 MHz   |
| Amplitude          | 10 V    |

Case 1: The 1 mm gap was open to air. SA-1 generated a swept sine wave from 1 Hz to 1 MHz and the signal amplitude detected by the SA sensor was measured by the oscilloscope.

Case 2: The 1 mm gap was filled with a few water drops. The rest of the process was all repeated as in Case 1.

**Figure 6** presents the amplitudes of the received sensor signal in two cases: (1) no water in the gap and (2) with water in the gap. The X-axis is a logarithmic coordinate of the frequency from 1 Hz to 1 MHz. The blue curve represents the sensor signal amplitude in case of no water. The red curve depicts the sensor signal amplitude in case of water presence in the gap. When there was no water in the gap, the stress wave could hardly propagate through the air gap from the SA actuator to the SA sensor. Therefore, the amplitude of the received signal was very low. However, when the gap was filled with water, water changed the wave impedance and functioned as a conduit of the stress wave, and much more stress wave energy traveled through the gap. The amplitude of the received signal dramatically increased in the frequency range 50–200 kHz. This test verified that the amplitude of the sensor signal corresponds to the crack and the water presence in the crack.

### 3.3.2. Water-quantity detection

In this test, SA-1 (actuator) was embedded into a small concrete cylinder before casting and SA-2 (sensor) was fixed by a cramp outside the concrete shown in Figures 7 and 8. There is a water layer between these two SAs. SA-1 generated a swept sine wave from 1 Hz to 1 MHz and SA-2 detected the signal response. The depths of the water between the concrete and SA-2 were set in three cases: (1) 1 mm, (2) 2 mm, and (3) 3 mm.

**Figure 9** shows the amplitudes of the received signal corresponding to different water depths. The amplitudes of the sensor signal show a proportional trend of decreasing voltage vs. increasing water depth. This test verified that the amplitudes of the sensor signal correlated with the water quantity between SAs.
From the two simple experimental verifications, the active sensing approach successfully detected the case of water migrating in the crack. Water in the crack strengthened the stress wave propagation. Moreover, the verified tests provided potential feasibility to quantitatively monitor the water amount existing in the crack.

Figure 7. Test setup: (a) concrete specimen with an embedded SA; (b) concrete specimen with an external SA.

Figure 8. Diagram of quantitative water detection.

Figure 9. Amplitudes of the sensor signal with different water depths.

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4. Experimental setup

4.1. Experimental procedures

Case 1: Concrete beam without cracks

In the experiment, a concrete beam (18” × 6” × 3”), as shown in Figure 10, was casted in the laboratory. Three SAs were embedded in predetermined locations before casting. SA-0, as the actuator, was placed in the middle of the concrete beam. SA-1 and SA-2, as sensors, were placed 2 inches from the ends of the concrete beam. The rebar on the bottom of the concrete beam was used to enhance the strength of the concrete beam. The location of the embedded SAs in the concrete beam is shown in Figure 11.

Case 2: Concrete beam with a large crack

A load test was conducted to artificially form a crack in the concrete beam, as shown in Figure 12. A continuously increasing load was applied to the concrete beam. After the loading process, an artificial crack was generated in the concrete beam, as shown in Figure 13.

Case 3: Crack filled with water

In case 3, the whole concrete beam was stored in a water environment for 24 hours. Therefore, the water completely filled in the concrete crack and the boundary condition of the concrete
beam was stable. Figure 14 is a photograph of the concrete beam stored in the water environment.

4.2. Excited swept frequency sine wave signal

In this experiment, SA-0 was used as the actuator to generate the desired swept sine wave using an Agilent 33120A function/arbitrary waveform generator. The detailed parameters of the guided wave are shown in Table 2, while the graph of the swept sine wave for 0.3 second of data is shown in Figure 15.

5. Experimental results

5.1. Time domain analysis

In each case mentioned above, SA-1 and SA-2 were both used as sensors to detect the stress wave generated by SA-0. The received sensor voltage plots, as shown below in Figure 16, demonstrated the sensor signal response. Figure 16(a), (c), and (e) corresponds to SA-1 while Figure 16(b), (d), and (f) corresponds to SA-2. Each of the signal graphics contained two periods of the sensor signal according to the swept excitation sine wave. Owing to the artificial crack between SA-0 and SA-1, the stress wave propagation was

| Start frequency | 100 Hz |
|-----------------|--------|
| Stop frequency  | 150 kHz|
| Sweep period    | 3 s    |
| Amplitude       | 10 V   |

Table 2. Detailed parameters of the swept sine wave signal.
extremely weakened and no signal response was detected. When the crack was filled with water, water changed the wave impedance and strengthened the stress wave propagation. As a result, the amplitude of the received signal increased, as shown in Figure 16(e). Figure 16(b), (d), and (e) presents the signal responses of SA-2. Compared with the crack...
existence condition between SA-0 and SA-1, no crack formed between SA-0 and SA-2. However, when comparing Figure 16(d) to Figure 16(b), Figure 16(d) demonstrates the same voltage level but a different signal response from the sensor voltage graphic. Figure 16(f) indicates a slight voltage value drop when the concrete beam is placed in the water environment. The reason is the boundary condition of the stress wave propagation change in both cases. Although the stress wave propagation between SA-0 and SA-2 is not directly related to the crack and water, the received stress wave response is still slightly influenced by the boundary condition change.

5.2. Wavelet packet analysis: sensor energy index
Based on the energy vector calculation using wavelet packet analysis, the received sensor energy values are presented in Figure 17. For SA-1, a sensor energy trend is demonstrated in each case. Without the crack and water, the received sensor energy level is close to $10^5$, as shown with the left-most blue bar. The large crack in the concrete beam reduces the sensor energy to the degree of $10^2$, as shown with the left-most green bar. When the crack is filled with water, the sensor energy rises to the degree of $10^3$, as shown with the left-most brown bar. For SA-2, the boundary condition-induced energy change is negligible and the sensor energy maintains stable for all the cases, as seen in the right-hand portion of Figure 17.

6. Conclusions
In this paper, the SA-based active sensing approach is successfully developed to detect water presence in a concrete crack. The large crack in the stress wave path acts as a stress relief and attenuates the transition energy from the actuator to the sensor. Therefore, the amplitude of the received sensor voltage significantly reduces. However, in the case of water presence in the concrete crack, water changes the wave impedance and guides the excited stress wave to propagate through the crack. The water presence in the concrete crack can be confirmed by the increase of the received sensor signal amplitude. In addition, the wavelet packet-based energy index in this research quantitatively indicates the received sensor energy level corresponds to different concrete conditions such as health status, large crack damage and water presence in the concrete crack.

![Figure 17. Sensor energy performance of SA-1 and SA-2 in three cases.](image-url)
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