Dual Mode Sensing on Grout Structures with Piezoelectric Sensors

Z. TIAN, L. YU, M. EL-BATANOUNY AND P. ZIEHL

ABSTRACT
Monitoring of cracking in low-strength grout structures is of high interest to owners and regulatory agencies associated with infrastructure safety. Due to the variety of deterioration sources and locations of defects in infrastructure materials, there is currently no single method that can detect and address the potential sources globally. In this paper, we present a dual mode sensing methodology that attempts to integrate passive acoustic emission (AE) and active guided ultrasonic wave (GUW) inspection methods based on the use of permanently installed piezoelectric sensors (PES). Active or growing cracks emit AE waves that arise from the rapid release of strain energy. Analysis of these recorded signals provides early stage information about the cracking source with very high sensitivity. The “active” SHM approaches, on the other hand, use one sensor in the array to generate interrogation waves and the others as the wave receivers. By that means, quantitative information regarding the structural state of health and integrity can be extracted. A set of proof-of-concept tests are performed on a small grout specimen with two types of PES transducers. Two array imaging algorithms are developed for AE source localization and active damage detection, respectively. The methods demonstrated in this investigation provide promising means for imaging of cracking events both passively and actively.

INTRODUCTION
Concrete structures have been widely used in civil engineering. Monitoring of defect in concrete structures is one of the important objectives of structure health monitoring. Due to the heterogeneous nature of the cement-based materials, the ultrasonic waves in concrete exhibit highly scattering and attenuation, leading to the difficulty of concrete damaged detection. Grout is a material that is often considered as "concrete without aggregate" and used in reinforced masonry as a bonding substance. Technically it is a fluid mixture of cement, aggregates and water [1]. In history grout

Zhenhua Tian, Mechanical Engineering, Univ. of South Carolina, Columbia, SC, 29208
Lingyu Yu, Mechanical Engineering, Univ. of South Carolina, Columbia, SC, 29208
Mohamed EL-Batanouny, Civil Engineering, Univ. of South Carolina, Columbia, SC, 29208
Paul Ziehl, Civil Engineering, Univ. of South Carolina, Columbia, SC, 29208
is used to tie the masonry walls and steel bars together, in effect creating a reinforced concrete structure. Grout is classified as either fine or coarse depending on the size of aggregate used. Allowable aggregate size is based on dimensions of the grout space to be filled and the height of space to be grouted [1].

As a passive structural health monitoring (SHM) technique, acoustic emission (AE) has been applied with success for real time monitoring of concrete structures [2-4]. Figure 1a illustrates the “passive” AE sensing concept [5]. Active or growing cracks emit AE waves, which are transient stress waves that arise from the rapid release of strain energy following micro-structural changes in a material [6]. AE waves can be recorded by means of sensors placed on the surface of a structure. AE signals provide information about the source of the AE with very high sensitivity.

The “active” SHM approaches, on the other hand, use an actuator to generate interrogation waves and a receiver to detect and assess the damage in the structure. Among various active SHM methods, ultrasonic testing remains the workhorse [7]. Figure 1b illustrates the “active” ultrasonic sensing concept [5]. Active sensors interact directly with the structure and find its state of health and integrity.

This paper explores the dual mode sensing ability of a single sensor network for grout and similar structures. The dual mode sensing consists of passive AE and active guided ultrasonic wave (GUW) sensing technologies [8]. Two types of piezoelectric sensors (PES), a resonant type AE transducers and a broadband type PZT wafer sensors are used. The former are used in the passive mode while the latter are used in both passive and active modes. A proof-of-concept test is performed on a small grout specimen. For passive sensing, AE event is simulated by pencil lead break (PLB) while for active sensing, the damage is simulated by a drill hole.

### PIEZOELECTRIC SENSORS

Two types of PES, a resonant type AE sensors and a broadband PZT wafer sensor are used in this study. The resonant type AE sensor, PAC R6i*, is a conventional AE sensor that is made of piezoelectric crystals. The PZT wafer sensors have been widely used in aerospace SHM applications due to their small size, light weight, and relatively low cost. They are used for both passive and active sensing in this work. The R6i is well established AE transducers while the PZT sensors despite being successful in GUW applications are new for AE sensing. In this study, R6i will be used only for AE sensing, as a comparison to the PZT wafer sensors.

### R6i AE Sensors

The R6i sensor is a 60 kHz resonant AE sensor which has a build-in integral preamplifier of 40 dB. These integral pre-amplifier sensors eliminate the need for
cumbersome pre-amplifiers by incorporating two functions into one, thereby reducing equipment costs and decreasing set-up time for field applications. Due to the high sensitivity and low resonant frequency properties, R6i can be used for applications such as metal, composite and concrete structures.

R6i sensors are generally used in the passive sensing mode. The detection/measurement of an AE signal is usually referred to as a hit. Each AE hit is associated with a waveform where a number of AE parameters can be measured. These parameters include amplitude, duration, counts, average frequency, signal strength and others. Figure 2 illustrates the schematic for an AE hit.

![AE waveform schematic](image)

**Figure 2 AE waveform schematic**

**PZT Wafer Active Sensors**

Among various ultrasonic transducers, PZT sensors are considered as the enabling component of SHM in aerospace applications due to their small size and light weight which allow them to be used in a large quantity. PZT sensors operate on the piezoelectric principles that couple the mechanical and electrical properties of the material. PZT sensors generate an electric field when they are subjected to a mechanical stress (direct effect), or, conversely, generate a mechanical strain in response to an applied electric field. Hence, PZT sensors can be used as both actuators and sensors.

In this study, the APC 850 PZT sensors are used. Figure 3 shows the piezoelectric principles of these sensors. When the applied electric field $E_3$ is parallel to the spontaneous polarization $P_s$ in $x_3$ direction, the PZT wafers will generate a lateral (in plane) contractions $\varepsilon_1=d_{31}E_3$ and $\varepsilon_2=d_{32}E_3$ (always $d_{31}=d_{32}$). Therefore, they can be used to produce in-plane motion. A detailed description of the use of PZT sensors can be found in [9].

![Piezoelectric principles and in-plane strain excitation of a PZT wafer](image)

**Figure 3 Piezoelectric principles and in-plane strain excitation of a PZT wafer**

**DUAL MODE SENSING WITH PES**

**The Sensing Methodology**

As a passive SHM technique, AE is known being effective for cracking event detection at very early stage. When propagating along the structure, the transient AE
waves can be recorded by the PES. The recorded AE signals can provide information about the AE source with very high sensitivity. However, one limitation with AE is that it cannot quantify the crack. For example, it cannot provide the crack size information.

The active GUW directly probes the structural health state and quantitatively detect the damage. The active GUW approach uses an actuator to generated interrogation waves to diagnose the structure and a receiver to detect and assess the health state of the structure. However, it is known that active approach has a higher energy consumption compared to the passive one. In addition, the detectable size of the crack is limited by the GUW wavelength.

Hence, we have strategically proposed to used a combined passive and active sensing scheme that takes advantages of AE and GUW approaches for crack damage detection and monitoring [5]. In the work presented here, we explore the possibility of a dual mode sensing by using a single sensor array. That is to say, the same sensor array switches between passive AE and active GUW sensing modes. During a SHM process, the PES sensor array stays in the passive mode waiting for the AE events and detects them when occur. When and only when significant AE events are detected, the sensor array then switches to the active mode to conduct GUW interrogation. Otherwise, the PES array will stay in the passive mode for AE detection. The schematic for the dual mode sensing is illustrated in Figure 4.

![Figure 4 Piezoelectric principles and in-plane strain excitation of a PZT wafer](image)

### Experimental Tests

To verify the dual mode sensing capability of the PES array, a set of proof-of-concept tests are conducted. A square grout slab of dimension 610 mm × 610 mm × 150 mm was prepared at the University of South Carolina Structural laboratory for dual mode sensing using R6i and PZT sensors. The slab was cast with a grout mix design provided by the Department of Energy (DOE) as shown in TABLE I. Four R6i sensors and four PZT sensors (diameter 7 mm; thickness 0.5 mm) were surface mounted on the specimen. Sensor configurations are shown in Figure 5. The sensor locations are listed in TABLE II.

![Figure 5 Schematic of the test specimen and damage (hole and PLB)](image)
TABLE I GROUT MIX DESIGN

<table>
<thead>
<tr>
<th>Material</th>
<th>Cement</th>
<th>Fly Ash</th>
<th>Sand</th>
<th>No. 67 stone</th>
<th>water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lb/yd³)</td>
<td>150</td>
<td>500</td>
<td>1850</td>
<td>800</td>
<td>415</td>
</tr>
</tbody>
</table>

TABLE II PES SENSOR LOCATIONS

<table>
<thead>
<tr>
<th></th>
<th>R6i</th>
<th>PZT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors</td>
<td>R₁, R₂, R₃, R₄</td>
<td>P₁, P₂, P₃, P₄</td>
</tr>
<tr>
<td>x (mm)</td>
<td>400, 406, 210, 210</td>
<td>400, 410, 210, 206</td>
</tr>
<tr>
<td>y (mm)</td>
<td>168, 425, 178, 425</td>
<td>210, 406, 203, 406</td>
</tr>
</tbody>
</table>

TABLE III PASSIVE SENSING RESULTS.

<table>
<thead>
<tr>
<th></th>
<th>AE source localization</th>
<th>OR imaging</th>
<th>AND imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLB test location</td>
<td>R6i</td>
<td>PZT</td>
<td>R6i</td>
</tr>
<tr>
<td>X (mm)</td>
<td>254</td>
<td>254.3</td>
<td>254.7</td>
</tr>
<tr>
<td>Y (mm)</td>
<td>305</td>
<td>302.0</td>
<td>311.8</td>
</tr>
<tr>
<td>X error (%)</td>
<td>0.12</td>
<td>0.28</td>
<td>5.35</td>
</tr>
<tr>
<td>Y error (%)</td>
<td>0.98</td>
<td>2.23</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Figure 6 AE source location results: (a) using R6i sensors, (b) using PZT sensors.

PASSIVE SENSING

In passive sensing, both the R6i and PZT sensors are used. Four R6i sensors (R₁-R₄) were bonded to the grout structure and directly connected to the data acquisition system (sensor highway II*, Mistras Group, Inc.). Four PZT sensors were installed next to the R6i as illustrated in the layout. They were connected to the sensor highway through 40 dB broadband voltage pre-amplifiers†. PLB test using ASNT standard was performed at location (245 mm, 305mm) to simulate the AE source. The signals were recorded by the acquisition system and processed by both the AE source localization using AEwin† software and passive array imaging methods to locate the AE source.

AE Source Localization

Passive AE source localization method can detect and locate damage within the structure when the formation of the damage generates a stress wave that causes sensors to become excited. We first use the AE source localization method by AEwin software to detect the simulated AE source. Figure 6 shows the localization results for R6i sensors and PZT sensors, respectively. The sensing results are listed in TABLE 3. The results are in consistent with the PLB test location. Both the R6i and PZT successfully detected the AE source though PZT yielded larger localization error.

† http://www.pacndt.com/
Passive Array Imaging

Using a novel passive array imaging method, the location of AE source can also be determined and further visualized as an inspected image [8]. The passive array imaging algorithm uses a network of sensors spatially distributed along the structure that receives the AE signals. The image construction process is based on a synthetic time reversal concept by shifting back time difference signals to their time origin. Two sets of data processing algorithms, the AND and OR logic, have been developed [8]. In this test, the imaging algorithms were used to process both R6i and PZT sensor AE signals to construct intensity images which can indicate AE location. The imaging results using both AND and OR algorithms for both the R6i array and PZT array data are shown in Figure 7 and Figure 8, respectively. The results show that each imaging algorithm has its own advantage and disadvantage. The AND logic has higher sensitivity since it requires positive detection from all measurements. However, if any false detection is made with the AND logic, a case of true damage detection will be immediately missed. The centers of the highlighted areas (maximum intensity) are listed in TABLE 3. They are in consistent with the PLB test location.

![Figure 7 Passive array imaging using R6i sensors: (a) OR logic; (b) AND logic.](image1)

![Figure 8 Passive array imaging using PZT sensors: (a) OR logic; (b) AND logic.](image2)

ACTIVE SENSING

When there are significant AE events in the structure, the sensing system will switch to the active sensing mode to directly interrogate the structure and quantitatively evaluate the damage. Since the PZT sensors can be used as both actuators and sensors, the same PZT array (P1-P4) is used to perform an active imaging on the damage.
In the active sensing, the PZT sensors are either connected to a function generator (Hewlett Packard 33120A) serving as a wave actuator or to an oscilloscope (Tektronix 5034B) channel serving as the receiver. Each time one PZT sensor is used to generate Rayleigh waves for interrogation, while all the others are used as the wave receivers. All sensors work in a round-robin pattern. The interrogation signal is a three count toneburst with a certain carry frequency. A power amplifier (Krohn-Hite 7602) is used to increase the excitation voltage to 100 V.

Prior to introducing the damage, reference signals were recorded from the pristine structure denoted as the baseline information. Then, the damage was introduced by drilling a hole of 25 mm diameter and 76 mm depth onto the grout structure at the location (245 mm, 305mm). A new set of data were recorded denoted as measurements. The scatter signal is then acquired by taking the difference between the baseline and measurements. Note that we assume that the damage is the only source that causes the ultrasonic wave signal change (excluding environmental fluctuation and operational deviation, etc.). Hence, the scatter signal is correlated to the damage present in the structure and can be used to evaluate the damage location and severity with active array imaging algorithms [10, 11]. For example, Figure 9a shows the signals recorded from the pristine structure and the damaged structure from the transmitter and receiver pair $P_1$-$P_2$, respectively. Figure 9b shows the scatter signal from the damage.

After data acquisition, the damage image was constructed based on active array imaging algorithms [10, 11]. Figure 10a is the result obtained from the OR algorithm. Due to the summation operation, the illumination at the damage location is intensified by the contribution of scatter signals obtained from all transmitter-receiver paths. Although the background noise is intensified, but the damage can still be identified as the most illuminated spot in the image, around the location (248 mm, 312 mm) with acceptable errors (2.3%, 2.2%). With the AND algorithm, the damage is identified at
the location (248 mm, 312 mm) in Figure 10b, but with background noise mostly removed through the multiplication operation.

CONCLUSIONS

This paper explores the dual mode sensing capability of PES arrays that can detect surface damage in grout structure using the Rayleigh surface waves. The dual mode sensing strategically integrates passive AE and active GUW inspection. For proof of concept, a set of combined AE and GUW tests have been conducted. In the passive AE mode, PZT array demonstrated equivalent performance to the commonly used R6i AE transducers in using AEwin software as well as passive array imaging. This shows the potential of using low-cost low-profile low-weight PZT sensors for AE sensing on grout structures. In the active mode, PZT array successfully imaged the location of a drill hole with satisfying error. While this specific investigation is focused on the particular case of damage detection and imaging in low strength grout, the techniques and approaches are equally applicable to the detection of damages in mass concrete placements for a large number of applications including those related to major bridge and building foundations.

ACKNOWLEDGEMENT

The authors would like to acknowledge the funding support from University of South Carolina Advanced Support for Innovative Research Excellence ASPIRE I grant by the Office of the Vice President for Research.

REFERENCES