Adaptation of PWAS Transducers to Acoustic Emission Sensors
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Abstract: Piezoelectric wafer active sensors (PWAS) are non-intrusive transducers that can convert mechanical energy into electrical energy, and vice versa. They are well known for their dual use as either actuators or sensors. Though PWAS has shown great potential for active sensing, its capability for acoustic emission (AE) detection has not yet been exploited. In the reported work, we have explored the implementation of PWAS transducers for both passive (AE sensors) and active (in-situ ultrasonic transducers) sensing using a single PWAS network. The objective of the work presented in this paper is to adapt PWAS as AE sensors and compare it to the commercially available AE transducers such as PAC R15.

An experiment has been designed to show how PWAS can be used for AE detection and the results were compared to a standard AE sensor, PAC R15I. Tests on compact tension specimens have also been conducted to show PWAS capability to pick up AE events during fatigue loading. PWAS field installation technology has been tested with packaging similar to that used for traditional strain gauges. The performance of packaged PWAS has been compared with that of conventional AE transducers R15I. We have found that PWAS not only can detect the presence of AE events but also can provide a wide frequency bandwidth. At this stage, PWAS underperforms the commercial AE sensors. To make PWAS ready for field test, signal to noise ratio needs to be significantly improved.

Keywords: Piezoelectric Wafer Active Sensors, PWAS, R15I, Acoustic Emission Sensor, Bridge Health Monitoring

1 INTRODUCTION

According to the Federal Highway Administration (FHWA) National Bridge Inventory (NBI) of 2007, the number of structurally deficient and functionally obsolete bridges is 72,524 and 79,792, respectively. While there are about 10,000 bridges being constructed, replaced, or rehabilitated annually in the United States at a cost of over $5 billion, the total annual costs including maintenance and routine operation are significantly higher [1]. As the inventory continues to age, routine inspection practices will not be sufficient for the timely identification of areas of concern and to provide enough information to bridge owners to make informed decisions for safety and maintenance prioritization. Continuous monitoring is needed for long term evaluation; monitoring areas of concern, such as retrofits, previous repairs or monitoring an area with known flaws, while scheduling and awaiting a repair or continuous monitoring for bridge impacts (ship or vehicle). Continuous monitoring can also be used in cases where there is a concern about vandalism, terrorism, and/or bridge element integrity. Therefore, monitoring of fatigue cracking in steel bridges is of interest to many bridge owners and agencies.

1.1 STEEL BRIDGE MONITORING WITH ACOUSTIC EMISSION

The monitoring of fatigue cracking in bridges has been approached with acoustic emission using either resonant or broadband sensors. Acoustic emission monitoring has shown to be able to detect crack growth behavior [2-11] and assess integrity of structures such as bridges and aircraft [12-15]. The method has the notable advantage that the precise location of cracking does not need to be known for evaluation purposes.

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Rather, the sensors together with appropriate algorithms are capable of locating and quantifying active crack activity. It has been reported that acoustic emission techniques are so sensitive that fatigue cracks can be detected successfully even though the crack length may be less than 10µm [4,6].

One of the challenges in passive monitoring is the discrimination of crack signals from noise signals. Acoustic emission from grating can be minimized by collecting and analyzing signals just around the peak load [2,9]. The spatial filtering techniques based on the source location, guard transducers [5,16] and time of arrival [17] can be employed to separate extraneous noise from crack bursts in laboratory testing to understand the mechanism of acoustic emission associated with crack growth behavior, based on the prediction that the crack initiates ahead of the notch tip and grows along the notch plane. However, the techniques used to minimize extraneous noise in laboratory testing may not be entirely applicable to acoustic emission bridge-monitoring because the crack location, the environmental noise and loading amplitudes can be less predictable in the field.

1.2 Piezoelectric Wafer Active Sensors

Historically, AE signals have been captured with special-purpose AE sensors, which are costly. Conventional AE sensors are made of piezoelectric crystals as the sensing elements which are encapsulated for protection and coupled together with a wear plate for good acoustic coupling. The frequency content and sensitivity of the sensor are controlled by the geometry and properties of the piezoelectric crystal.

In the work described here, we intended to adapt the piezoelectric wafer active sensors (PWAS) for steel structure fatigue crack acoustic emission detection [18]. PWAS as an active sensing device work on the piezoelectric principles. They can be permanently attached to the structure to interrogate at will and can operate in propagating wave mode. PWAS have been commonly used for ultrasonic guided waves excitation and detection in the fields of nondestructive evaluation and structural health monitoring. Dupont et al. studied the possibility of using embedded piezoelectric wafer sensors to detect AE signals in composite materials [19].

To illustrate the capability of PWAS to detect AE signals in metallic structures, we performed several experiments on the rectangular aluminum plate specimen of 1-mm thickness as shown in Figure 1a, on which a network of PWAS was installed. AE events were simulated by pencil lead break method (PLB) using the fracture of a mechanical pencil leads on the specimen surface. Table 1 shows the location of the PWAS and their radial distance from the AE event. The simulated AE signals captured at PWAS 1, 5, 7, 9 are shown in Figure 1b. The signal on PWAS 7, closest to the AE source, is the strongest. This signal displays both high-frequency and low-frequency components, corresponding to S₀ (axial) and A₀ (flexural) waves, respectively. The flexural waves display much higher amplitudes than the axial waves, although their travel speed is slower. The signals received at the other PWAS display similar trends, although of lower amplitudes, due to their greater distance from the AE source. These experiments have proven that the PWAS transducers are capable of detecting AE signals. The high sensitivity of these sensors is remarkable because signals of up to ±0.5 V were directly recorded on a digital oscilloscope without the need for any signal conditioning/pre-amplifiers.
Figure 1  PWAS acoustic emission detection. (a) geometry of the experiment: the location of PLB was at point \( x_P = 400 \text{ mm}, y_P = 200 \text{ mm}; \) (b) typical AE signals: the signals were spaced up by vertical shifts for display.

Table 1  Location of PWAS transducers by position \((x, y)\) and radial distance, \(r\), from the acoustic emission (AE) events. Note that the time of flight (TOF) was adjusted by 76.4 \( \mu s \) to account for oscilloscope trigger.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Distance (mm)</th>
<th>TOF for ID ((\mu s))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( x )</td>
<td>( y )</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>7</td>
<td>450</td>
<td>250</td>
</tr>
<tr>
<td>9</td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td>Reconstructed ID event</td>
<td>402.5</td>
<td>189.6</td>
</tr>
<tr>
<td>Actual AE/ID event</td>
<td>400</td>
<td>200</td>
</tr>
</tbody>
</table>

Though it is been shown that PWAS can be used as a passive sensor to detect impact or acoustic emission, its performance and readiness for field application have not been completely evaluated. In order to utilized PWAS for AE applications the following challenges have to be addressed:

- PWAS sensing on the host steel structures
- PWAS AE detection calibration
- Noise and signal-to-noise (SNR) investigation
- Identify the barriers of extending previous success on plate/pipe structures to infrastructure sensing and monitoring

In the subject project, we will adapt PWAS as AE sensors to detect sounds with frequency components higher than 150 kHz where the acoustic signals propagating with minimal attenuation and minimal background noise due to the rubbing of structural components.
2 PWAS AE DETECTION ADAPTATION

A set of comparison tests were conducted to evaluate the sensitivity of PWAS in comparison with the typical commercial AE sensor R15I**. Two specimens were used. One is a 1.6 mm thick rectangular 2024 aluminum plate (25 mm by 25 mm); the other is a 19 mm thick square steel panel (25 mm by 25 mm). Both specimens were installed with 7-mm round 0.2 mm thick PWAS (APC850) using M-200 adhesive following the standard installation used by strain gauge.

Test setup is illustrated in Figure 2, unless otherwise specified. The PAC DiSP system was used to perform the data collection. PWAS was connected to a 2/4/6 preamplifier with 100-1200 kHz built-in filter and gain set at 40 dB; then to channel 1. R15I was connected directly to DiSP and has a built-in internal preamp set at 40 dB as well. R15I was glued on the structure and connected to channel 2. AE was simulated by PLB method, performed at either plate edge or plate surface. Rubber gloves were used to avoid causing disturbance by touching the plate.

![Testing specimen](image1)

(a) AE testing experimental setup. (a) Test setup schematic; (b) laboratory test setup.

2.1 ALUMINUM PLATE TESTS

First the test was performed on a 2024 aluminum plate with 1.6 mm thickness. PWAS and R15I were installed following the setup described previously. The specimen was subjected to two different modes of acoustic emission by PLB: (a) out-of-plane (OOP) and (b) in-plane (IP). Distances from PLB to R15I and PWAS are equals. To make sure the measurements were reproducible, the experiment was repeated a few times, as given in Table 2.

PWAS and R15I detected all PLB with comparable waveforms. One set of AE signals (3rd test in Table 2) detected by R15I and PWAS in time domain and their frequency spectra are given in Figure 3. Signal amplitudes were the same at the two sensors, around 78 dB. PWAS shows a crisper response in the earlier part of the waveform when the fundamental symmetric mode and antisymmetric mode are arriving with a time separation of approximately 20 μs. An expanded view of the early PWAS response is shown in Figure 4a with the theoretical out-of-plane point motion for PLB given in Figure 4b (PlotRLQ). The agreement is very good. The agreement between observation and theory is especially good for the fundamental symmetric mode (earliest part of the response). The biggest differences between the measured and theoretical waveforms are the relatively abrupt fall-off in the observed signal shortly after it reaches peak amplitude, and its ragged appearance at the high frequency beginning of the arrival.

Noise measured by R15I and by PWAS is shown in Figure 5. The measurement parameters, setup, and measured quantities are summarized in Table 2. Based on the comparison, it can be seen that PWAS has comparable measurements on the 1.6-mm aluminum plate compared with R15I.

Table 2  AE detection on 1.6-mm aluminum plate.

<table>
<thead>
<tr>
<th>PLB (mm)</th>
<th>PLB type</th>
<th>PWAS recorded dB</th>
<th>R15I recorded dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>OOP</td>
<td>83</td>
<td>82</td>
</tr>
<tr>
<td>0.5</td>
<td>OOP</td>
<td>89</td>
<td>89</td>
</tr>
<tr>
<td>0.3</td>
<td>OOP</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>0.3</td>
<td>IP</td>
<td>88</td>
<td>86</td>
</tr>
<tr>
<td>0.3</td>
<td>IP</td>
<td>84</td>
<td>78</td>
</tr>
</tbody>
</table>

Figure 3  PLB simulated AE detection on 1.6-mm aluminum plate. (a) R15I measurement and its spectrum; (b) PWAS measurement and its spectrum

Figure 4  Detailed analysis of PWAS response. (a) Measured PWAS output; (b) theoretical curve for the PLB.
2.2 Steel Plate Tests

On the 19 mm steel plate, two PWAS, numbered as #1 and #2, were used. Positions of PWAS and R15I are given as shown in Figure 6. PLB was performed on two locations, PLB AE 1 and PLB AE 2 as shown in Figure 6. Position 1 is the mid-plane on the plate edge in order to generate IP stress wave while position 2 is on the surface to generate OOP wave.

![Figure 6 Steel specimen instrumented with PWAS and R15I.](image)

2.2.1 Surface AE detection

In-plane detection was performed on the surface (i.e., PLB AE 1(405,355)). A 0.5-mm pencil lead break was performed. Distances from PLB to R15I and PWAS #1 are 98.2 mm and 72.11 mm, respectively. Both R15I and PWAS #1 detected the AE with amplitude at 89 dB and 75 dB, respectively. Hit times were 1.5 μs apart. Both waveforms were well captured as presented in Figure 7. This confirms PWAS validity on AE detection on the thick steel plate.

Also noticed from the test is, though low in SNR on the thick steel plate, PWAS does provide a much wider frequency response to PLB AE which cannot be obtained from R15I.
2.2.2 Edge AE detection

IP AE detection was performed with the breakpoint at the mid-plane on the plate edge (i.e., PLB AE 2 (610,400)). Distances from PLB to R15I and PWAS #1 are 269.3 mm and 168.0 mm, respectively. Two 0.5-mm PLB were performed. R15I detected both. PWAS #1 did not detect either.

3 COMPACT TENSION TESTING

Compact Tension (CT) specimens made of structural steel A572 grade 50, the same material for the aforementioned 19 mm steel plate, were used in this study. The geometry of the specimens is displayed in Figure 8a. Custom fixtures were designed and fabricated to mount the CT specimens. The cyclic tension loads of minimum 1 KN and maximum 50 KN were applied to the specimen using servo hydraulic mechanical testing machine (810 Material Test System). Fatigue tests were conducted under load-controlled mode with frequency of 1 HZ. A clip gage was employed to measure the crack mouth opening displacement (CMOD) to clarify crack opening and closure and to determine the magnitude of the CMOD. The surface cracks were also monitored optically with a high resolution recording microscope. Two different pre-amplifiers, one with the bandpass filter in the range of 100-200 kHz and the other with wideband BP-SYS, have been used.

The comparison of crack localization analyzed by PAC AEwin software between PWAS AE sensor and commercially available R15I during CT testing is shown in Figure 9. With R15I, 1171 AE events were detected before the final failure, while 54 were detected by PWAS. Figure 9a gives the cumulative acoustic energy of R15I and PWAS together with the crack opening displacement. While PWAS detect a fewer number of acoustic activities, they detect the crack growth when the crack size reaches 0.83 mm. From Figure 9b, it can be seen that PWAS localization is closer and concentrated around the crack tip compared with the R15I detection in Figure 9c.
Figure 8  AE detection on a ½” CT specimen. (a) Geometry of the specimen and arrangement of transducers; (b) a snapshot of the actual specimen. AE PWAS are circled (rest are for active sensing). The R15I was installed on the other side of the specimen.

Figure 9  Comparison of crack localization in CT test on ½” steel specimen. (a) Cumulative acoustic energy by PWAS and R15I; (b) cracking detection and localization by R15I; (c) cracking detection and localization by PWAS
4 CONCLUSIONS

It is well recognized that, as the national highway and off-system bridge inventory continue to age, routine inspection practices will not keep pace with the demands. Continuous monitoring is needed for long term evaluation from an integrated sensing system that would act as a monitoring and early warning alarm system and be able to communicate the information from the bridge directly to the bridge owners for potential and immediate action. The subject NIST project incorporates novel active and passive sensing approaches based on the piezoelectric wafer active sensors to reduce the dramatic uncertainty inherent into any inspection and maintenance plan. One research thread presented hereby is focused on the adaptation PWAS transducer for acoustic emission measurement.

A demonstration system has been constructed on both thin aluminum plate and thick steel plate to validity PWAS as an AE sensor. PWAS measurements were compared to those obtained from commercial R151. Their measurements on thin aluminum are well correlated with the theoretical prediction for the capture of the fundamental symmetric mode. It is seen that PWAS can perform as efficient as R151 on a thin aluminum plate but less efficient on a thick steel plate. To make PWAS ready for field test, signal to noise ratio needs to be significantly improved. It is also found that PWAS provide wider frequency responses. Tests on compact tension specimens have also been conducted to show PWAS capability to pick up AE events during fatigue loading tests.

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6 REFERENCES


