In-situ Health Monitoring on Steel Bridges with Dual Mode Piezoelectric Sensors
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ABSTRACT

Current routine inspection practices for bridge health monitoring are not sufficient for timely identification of areas of concern or are incapable of providing enough information to bridge owners to make valuable informed decisions for maintenance prioritization. Continuous monitoring is needed for long-term evaluation from an integrated sensing system that would act as a monitoring and early warning alarm system that is able to effectively communicate the information from the bridge directly to the bridge owners for potential and immediate response. Due to the variety of deterioration sources and locations, currently there is no single NDE method that can detect and address the potential sources globally.

To address the need of this urgent highway bridge health monitoring, a joint venture research has been initiated under the NIST Technology Innovation Program by incorporating a novel and promising sensing approach based on piezoelectricity together with energy harvesting to reduce the dramatic uncertainty inherent into any inspection and maintenance plan. One approach to damage detection and classification has been focused on the use of piezoelectric sensors (PES) at both active (ultrasonic NDE) mode and passive (acoustic emission) mode on steel bridge. The acoustic emission (AE) method has been shown the best potential for global bridge health monitoring while active sensing will provide additional quantification process. Two types of the PES have been studied to provide fundamental principles for their applications to steel bridges. Extensive laboratory investigation was performed supported by a theoretical modeling analysis.

Keywords: Piezoelectric sensors, dual-mode, acoustic emission, ultrasonic NDE, bridge health, diagnosis

1 INTRODUCTION

This research is sponsored by National Institute of Standards and Technology (NIST), the Technology Innovation Program (TIP), which incorporates novel and promising sensing approaches together with energy harvesting devices to reduce the dramatic uncertainty inherent into any bridge inspection and maintenance plan. By reducing uncertainty, it will become feasible to prioritize resources more efficiently, and to improve the overall reliability of the bridge network at an acceptable cost. The research is targeted to both steel and concrete bridges, including the development of novel sensors and sensor nodes, and of damage assessment algorithms.

One of the challenges in this research is focused on the use of fused sensor data with multiple sensor types to provide information related to the degradation state of the structure and its correlation to a global performance index. The Acoustic Emission (AE) detection method has been shown the best potential for global bridge health monitoring, but has not been exploited to date. On the other hand, combining AE with additional guided ultrasonic waves (GUW) method will strengthen the proposed damage detection process. Using the GUW method, wide coverage could be achieved from a single location. In the project, the University of South Carolina, in collaboration with Mistras Group, Inc. (leading organization), are focused on the development of dual use piezoelectric sensors for steel bridge fatigue crack detection. The combined schematic is using AE to detect the presence of fatigue cracks in steel bridges in their early stage since methods such as GUW are unable to quantify the initial condition of crack growth since most of the fatigue life for these details is consumed while the fatigue crack is too small to be detected. Once the crack growth is detected, GUW active sensing allows for the imaging and quantification of cracks in metallic structures in the absence of crack growth, which complements AE sensing that relies on damage progression for quantification.

2 PWAS-BASED SENSING FOR BRIDGE HEALTH MONITORING SYSTEM

The wafer type PES used in this research is a small non-intrusive piezoelectric wafer active sensor (PWAS) that can be permanently installed on the structure and performed with ultrasonic nondestructive evaluation (NDE) at
In the subject project, we are developing a dual mode sensing approach using the low profile wireless PWAS network with energy harvested from wind and/or ambient vibration energy (Yu et al., 2010). To minimize the energy consumption, it is envisioned that as few as four PWAS will be employed to monitor the crack development.

2.1 PWAS ADAPTATION AS AE SENSORS

Historically, AE signals have been captured with special-purpose AE sensors, which are costly and obtrusive. Conventional AE sensors are made of piezoelectric crystals as the sensing element which are encapsulated for protection and coupled together with a wear plate (for good acoustic coupling) and backing material (for damping the reflection from the crystal). The frequency content and sensitivity of the sensor are controlled by piezoelectric crystal and the backing material.

Dupont et al. (2000) studied the possibility of using embedded piezoelectric wafer sensors to detect AE signals in composite materials. On steel structures, we adapt PWAS as AE sensors for high frequency (>150 kHz) detection where the acoustic signals propagate with minimal attenuation and minimal background noise due to the rubbing of structural components.

Laboratory tests have been conducted to investigate the PWAS application as an AE sensor. A typical commercial R15I AE sensor was used to calibrate the measurements. Two specimens were used in the tests. One was a 1.6 mm thick 2024 aluminum plate and the other was a 19 mm thick A572 grade 50 structural steel panel. Both specimens were installed with 7-mm diameter, 0.2 mm thick round PWAS using M-200 bonding adhesive following the standard installation used by strain gauge. The R15I sensor was mounted using hot melt glue.

The test setup is illustrated in Figure 1. PAC DiSP™ system was used to perform data acquisition. PWAS was connected to a preamp then to channel 1. The preamp had a 100-1200 kHz built-in filter and could accommodate a signal amplification of 40 dB. The R15I sensor had a built-in internal preamp with a gain also at 40 dB and was connected to channel 2. AE events were introduced by pencil lead break (PLB). Rubber gloves were used to avoid causing electrical disturbance by touching the plate.

![Test setup schematic](image1.png)  
![Laboratory test setup](image2.png)  

Figure 1 AE testing setup. (a) Test setup schematic; (b) laboratory test setup.

2.1.1 Aluminum Plate Tests

In the first part of the work, a 1.6-mm thick aluminum plate, approximately 300-mm by 300-mm, was used for testing PWAS AE detection. PWAS and R15I were placed adjacent on the plate, about 165 mm away from the plate edge where the PLB was applied. In total, five PLB of various lead sizes were applied. The PWAS transducer detected all of them with comparable amplitudes to those captured by R15I, as summarized in Table 1.

![Waveforms and frequency spectra](image3.png)

Figure 2 shows the waveforms and the frequency spectra for the test described in the third row in Table 1. In this test, 0.5 mm HB pencil lead was broken at the edge of the plate in the out-of-plane direction (pressing down and springing up). The detected AE signal amplitudes of the two sensors were about the same (78 dB). The PWAS gave a peak signal of 2200 mV against a noise of 200 mV, resulting in a signal-to-noise ratio (SNR) of approximately 11

or 21 in dB. Compared to R15I waveform, the response of PWAS was conspicuously crisper in the earlier part corresponding to the S0 mode arrival which was followed by the arrival of slower A0 mode.

Looking at the AE waveforms by PWAS and R15I present in Figure 2, it is noticed though the two waveforms have comparable signal peak amplitudes, PWAS shows higher floor noise (circled part). For AE detection, it is necessary that the sensor shows good signal to noise ratio. In this case, floor noise for the PWAS is too high and needs to be decreased.

Table 1  
AE detection on the 1.6-mm aluminum plate.

<table>
<thead>
<tr>
<th>PLB size</th>
<th>PWAS AE amplitude (dB)</th>
<th>R15I AE amplitude (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 mm</td>
<td>83</td>
<td>82</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>89</td>
<td>89</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>88</td>
<td>86</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>84</td>
<td>78</td>
</tr>
</tbody>
</table>

Figure 2  
0.5 mm PLB detection on 1.6-mm aluminum plate. (a) PWAS AE waveform and its frequency spectrum; (a) R15I AE waveform and its frequency spectrum

2.1.2 Steel Plate Tests

The second part of the work was conducted on a 19-mm thick steel plate. 0.5-mm HB PLB was applied on the surface of the plate about 72 mm away from PWAS. The R15I transducer was glued on the plate with a distance of 98 mm from the PLB. PLB was detected by PWAS with an AE amplitude of 73 dB in contrast to the 87 dB detected by R15I. The waveforms and their frequency spectra are provided in Figure 3. The PWAS signal showed a strong negative-going spike accounting for the 73 dB amplitude, fitting in a 600 mV peak. The background noise was about 150 mV, resulting in a SNR of approximately 4 or about 12 in dB. The SNR of PWAS in steel plate was much lower than that in aluminum plate. By examining the frequency spectra, it can be noted that PWAS has major frequency components beyond 200 kHz, showing a wider frequency response compared to resonant type R15I AE sensor.
Figure 3 0.5 mm PLB detection on 19-mm steel plate. (a) PWAS AE waveform and its frequency spectrum; (a) R15I AE waveform and its frequency spectrum

2.1.3 PWAS Compact Tension Test

Compact Tension (CT) specimens made of the same material as the steel plate used in section 2.1.2 were used. The geometry of the specimens is displayed in Figure 4a. 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 an MTS810 servo-hydraulic mechanical testing machine. 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 separate sets of AE sensors, namely R15I and PWAS monitored the process, as well. They connected to the Sensor Highway II™ data acquisition system through preamps. The data from these two sets of sensors were analyzed separately with AEwin™5 software.

Figure 4 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 were installed on the other side of the specimen.

The results of crack localization from PWAS sensors and R15I sensors during CT testing are shown in Figure 5. R15I sensors detected 1,171 AE events prior to failure, while PWAS detected only 54 events. Figure 5a gives the cumulative acoustic energy of R15I and PWAS together with the crack opening displacement. While PWAS detected a fewer number of acoustic activities, they detected the crack growth when the crack size reaches 0.83 mm. As can be seen Figure 5c, PWAS localization was closer and concentrated around the crack tip compared with the R15I detection in Figure 5b. This was thought to be mainly due to the enhanced sensitivity of the R15I sensors, which can complicate source location in small scale laboratory specimens due to reflections.

Figure 5 Comparison of crack localization in CT test on 1/2" steel specimen. (a) Cumulative acoustic energy by PWAS and R15I; (b) cracking detection and localization by R15I; (c) cracking detection and localization by PWAS

2.2 PWAS Active Damage Detection

In the dual mode sensing schematic, after significant cracking has been identified by passive mode AE detection, active mode sensing using pitch-catch interrogation is evoked to quantify crack growth through damage index and array imaging. A PWAS network consisting of several sensors spatially distributed on the plate can be used to interrogate the plate with one sensor generating the guided wave and the others receiving the structural response.

We assume that cracking is the sole source of changes in the detected Lamb waves. Also being assumed is that the waves travel in straight paths in the plate structures. Hence, the objective of our Lamb wave signal analysis is to extract damage related characteristics from the measured sensory data. When an elastic Lamb wave is transmitted and travels through the structure, wave scattering occurs in all directions where there is a change in the material properties due to damage. The scatter signal is defined as the difference between the measurement during the development of damage and the baseline signal at the initial stage. One advantage of using scatter signals is to minimize the influence caused by boundaries or other structural features which would otherwise complicate the Lamb wave analysis. In this research damage index (DI) is defined as (Zhao et al., 2007):

$$DI = 1 - \frac{C_{XY}}{\sigma_x \sigma_y}$$

(1)

$C_{XY}$ is the covariance of $X$ and $Y$ given by:
\[ C_{XY} = \sum_{j=1}^{N} \left( X_j - \mu_X \right) \left( Y_j - \mu_Y \right) \]  
\[ \text{(2)} \]

Where \( \mu \) is the mean value and \( N \) is the length of the data set. \( \sigma_X \) and \( \sigma_Y \) are the standard deviations of \( X \) and \( Y \), respectively, with their product given as

\[ \sigma_X \sigma_Y = \sqrt{\sum_{j=1}^{N} \left( X_j - \mu_X \right)^2 \left( Y_j - \mu_Y \right)^2} \]

\[ \text{(3)} \]

For the active sensing implemented during the CT test presented in section 2.1.3, four PWAS were used to perform pitch-catch wave propagation interrogation, as marked and numbered in Figure 6a. Using the definition of damage index defined above, the DI curves were plotted at different crack length as shown in Figure 6b for all the pitch-catch paths. The DI increases when the crack grows. The detection along sensors P0 to P1 is most sensitive, followed by the one along sensors P1 to P3 since the paths are perpendicular to the crack development path. The increment of the DI curves is also well correlated to the crack growth under fatigue loading.

![Figure 6](image)

(a) AE detection on a 1/2" 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.

3 R15I ACTIVE SENSING

R15I, the conventional AE transducers in previously presented comparison test, represent a significant advancement for the field of AE by enclosing a low-noise 40 dB pre-amplifier inside a standard high sensitivity sensor. R15I also comes with an optional “Auto Sensor Test” capability designated with an “AST” suffix after the sensor model type (e.g. R15I-AST). The AST feature allows the AE systems to control a pulser that is integral to PAC AST equipped preamplifiers and the integral preamplifier sensors (with AST option). This allows for any AE channel to pulse the sensor, while the receiving electronics remains active. Therefore, R15I transducers can also be used as a pulser and a receiver at the same time. In the present research, we explored the potential of using R15I as active sensors to monitor the crack growth during CT testing.

A CT specimen identical to the one used in the passive AE test described above was used. Note there is an initial notch of 82.6 mm in the specimen. Five R15I were installed (Figure 7); the layout was the same as in the passive AE test. The crack growth during CT testing is shown in Table 2. A total of 13 crack sizes were measured. At each crack size, an active AST test was performed between all sensors in a round robin pattern. Transducer R1 pulsed 5 times with a pulse width of 10 \( \mu \)s and a pulse interval of 1s. The pulsing excited plate waves propagating in all directions in the structure. When arriving at another R15I transducer, the signal starts to be recorder after it reaches the data acquisition threshold of the DiSP system. The recording time is known as the \( \text{delta t} \) information during the data acquisition process. Both waveforms and \( \text{delta t} \) together with other related information are saved by the system. For illustration, two signals at crack sizes #4 and #13 received at transducer R5 are provided in Figure 8.
Table 2  The increment of the crack size by MTS machine

<table>
<thead>
<tr>
<th>Crack Stage No.</th>
<th>Crack Extension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.96</td>
</tr>
<tr>
<td>2</td>
<td>3.57</td>
</tr>
<tr>
<td>3</td>
<td>5.74</td>
</tr>
<tr>
<td>4</td>
<td>8.93</td>
</tr>
<tr>
<td>5</td>
<td>12.52</td>
</tr>
<tr>
<td>6</td>
<td>16.1</td>
</tr>
<tr>
<td>7</td>
<td>20.9</td>
</tr>
<tr>
<td>8</td>
<td>27.6</td>
</tr>
<tr>
<td>9</td>
<td>34.3</td>
</tr>
<tr>
<td>10</td>
<td>58.5</td>
</tr>
<tr>
<td>11</td>
<td>66.9</td>
</tr>
<tr>
<td>12</td>
<td>76.6</td>
</tr>
<tr>
<td>13</td>
<td>85.9</td>
</tr>
</tbody>
</table>

During testing of the compact tension specimen, crack growth was developed from the initial notch. For pulsing-receiving between R1 and R5 (referred as "with crack" pair), this created a diffracted path for wave propagating, as indicated by the solid arrow in Figure 8. That is to say, the wave propagation is from R1 to the crack tip and then from the crack tip to R5. But for others such as those between R1 and R2, R1 and R3, and R1 and R4 (referred as "without crack" pairs) direct wave propagation occurs at most stages of crack development (note that the crack growth stopped before the tip reached the path from R1 to R5), as indicated by the dashed arrows in Figure 9. The path between R1 and R4 will be broken when the crack increases to size #10. We calculated the apparent velocity of wave propagation as the ratio between the wave propagation distance and wave propagation time. Wave propagation time is obtained from the data acquisition system using the arrival time \( \Delta t \). The velocity calculated from the without crack pairs in the pristine specimen before the crack development and the velocity calculated from the ‘with crack’ pair throughout the crack development are plotted in Figure 9a and Figure 9b, respectively.

An interesting result can be observed from comparison of Figure 9a and Figure 9b. For ‘without crack’ pairs, the apparent wave velocity is around 4485 m/s (calculated at pristine and crack No. 9). However, for the ‘with crack’ pair R1 to R5, the situation is different. In the initial stage, when the crack is very small and the diffraction is...
negligible, the apparent velocity is also around 4000 m/s. But as the crack increased, the apparent velocity decreased and became approximately 2188 m/s. The comparison of these two situations is plotted in Figure 10. The possible reason for this difference in velocities could be that the diffraction caused by the crack between R1 and R5 decreases the energy arrived at R5, therefore delayed the time when the signal threshold of the DiSP system is passed, thus resulting in a larger $\delta t$ being recorded. This apparent delay in arrival of the received signal results in a decrease in the calculated apparent velocity. Further study need to be conducted to evaluate this finding and developed a full explanation of the phenomenon.

Figure 9  Apparent group velocity plots for various pulser-receiver pairs. (a) velocity calculated for ‘without crack’ pairs at pristine condition and at the condition for crack stage #9; (b) velocity calculated for ‘with crack pair’ starting from the pristine condition and then throughout the 13 crack growth stages

Figure 10  Comparison between the apparent velocity between transducer pairs without crack in their path (4485 m/s) and transducer pairs with crack in their path (2188 m/s)

4 CONCLUSIONS

The majority of our civil infrastructure (highways and bridges) was constructed in the 1950’s with a 50-year design life. Over the same time period, the average daily traffic and live load magnitude on the majority of bridges has increased significantly. The use of minimal maintenance funds is less than optimal and relies primarily on subjective and time consuming inspection techniques such as visual inspection due to the lack of affordable, easily deployable, and reliable monitoring systems. It is well recognized that, as the national highway and off-system bridge inventory continues to age, routine inspection practices will not keep pace with the demands.

The subjected 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. In the work presented in this paper, we explored the potentials of using piezoelectric wafer active sensors (PWAS) for passive AE detection and using conventional R15I AE transducers for active crack growth monitoring. This work lays the foundation toward the development of a wireless dual mode sensor network for online bridge health monitoring.

Our project incorporates novel and promising sensing approaches based on the piezoelectric active and passive sensing to reduce the dramatic uncertainty inherent into any inspection and maintenance plan. The self-
powered features of the system will translate in easy deployment. Built-in self-check capabilities will eliminate the need for routine sensor maintenance. By reducing uncertainty, it becomes feasible to prioritize resources more efficiently, and to improve the overall reliability of the bridge network at an acceptable cost. The improved sensing method coupled with AE and PWAS correlation are envisioned to provide better tools to estimate the remaining fatigue life, and will be validated through field demonstration. It also has the potential to be applied to concrete bridge structures.

5 ACKNOWLEDGMENTS

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