Steel Bridge Fatigue Crack Detection with Piezoelectric Wafer Active Sensors

Lingyu Yu¹, Victor Giurgiutiu¹, Paul Ziehl², Didem Ozevin³, Patrick Pollock¹

¹Mechanical Engineering Department, University of South Carolina, Columbia, SC 29208

²Civil Engineering Department, University of South Carolina, Columbia, SC 29208

³Department of Civil and Materials Engineering, University of Illinois at Chicago, Chicago, IL 60607

yu3@engr.sc.edu, giurgiut@engr.sc.edu, ziehl@cec.sc.edu,

ABSTRACT

Piezoelectric wafer active sensors (PWAS) are well known for its dual capabilities in structural health monitoring, acting as either actuators or sensors. Due to the variety of deterioration sources and locations of bridge defects, there is currently no single method that can detect and address the potential sources globally. In our research, our use of the PWAS based sensing has the novelty of implementing both passive (as acoustic emission) and active (as ultrasonic transducers) sensing with a single PWAS network. The combined schematic is using acoustic emission to detect the presence of fatigue cracks in steel bridges in their early stage since methods such as ultrasonics 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. Hence, combining acoustic emission with ultrasonic active sensing will strengthen the damage detection process. The integration of passive acoustic emission detection with active sensing will be a technological leap forward from the current practice of periodic and subjective visual inspection, and bridge management based primarily on history of past performance.

In this study, extensive laboratory investigation is performed supported by theoretical modeling analysis. A demonstration system will be presented to show how piezoelectric wafer active sensor is used for acoustic emission. Specimens representing complex structures are tested. The results will also be compared with traditional acoustic emission transducers to identify the application barriers.

Keywords: Piezoelectric wafer active sensors, PWAS, acoustic emission, active sensing, guided waves, 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, and includes 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 dedicated sensors (e.g. strain, temperature) will strengthen the proposed damage detection process. In the project, University of South Carolina, in collaboration with Physical Acoustics Corporation (PAC) (leading organization), will focus on the development of dual use piezoelectric wafer active sensors (PWAS) for steel bridge fatigue crack detection. The combined schematic is using acoustic emission to detect the presence of fatigue cracks in steel bridges in their early stage since methods such as ultrasonics 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. 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. Challenges in this part of work include

- PWAS adaptation for AE detection
- Excitation principles for PWAS on the host steel structures
- Optimal PWAS network configuration to maximize the detection reliability
- Identify the barriers of extending previous success on plate/pipe structures to infrastructure sensing and monitoring

These challenges will be addressed as part of the laboratory experiments. The integration of passive acoustic emission detection with active sensing will be a technological leap forward from the current practice of periodic and subjective visual inspection, and bridge management based primarily on history of past performance. The combination of different sensing techniques is realistically envisioned to greatly improve the reliability of damage detection, and provide the reward of optimized decision-making.

2 PIEZOELECTRIC SENSING BASED HEALTH MONITORING

PWAS are small non-intrusive piezoelectric wafers that can be permanently installed on the structure and perform nondestructive evaluation (NDE) at will; and that have provided very promising results on the damage detection of plate/pipe structures (Giurgiutiu 2008).

2.1 PWAS ACTIVE SENSING ON ALUMINUM PLATE

In active mode, PWAS couple their in-plane motion with the particle motion of Lamb waves (guided waves propagating in plate) on the material surface, which is excited by the applied oscillatory voltage through the d_{31} piezoelectric coupling coefficient. When Lamb waves are guided between the two parallel free surfaces, the upper and lower surfaces of the plate, two basic types of Lamb waves can exist: symmetric mode (S_0 , S_1 , ...) and antisymmetric mode (A_0 , A_1 , ...). For each type, a number of modes may exist, corresponding to the solution of the Rayleigh-Lamb equation. Lamb waves are also highly dispersive and their speeds depend on the product of the frequency and the plate thickness.

Using propagation guided wave method, wide coverage could be achieved from a single location. The embedded PWAS guided method follows the general principles of conventional Lamb wave NDE. One PWAS transducer attached to the structure acts as transmitter and another PWAS at a different location as detector of guided Lamb waves traveling in the structure. The wave sent by the transmitter is scattered and altered at the structural discontinuity such as a crack. The scattering wave is then captured at the receiver. To ensure the crack detection, an appropriate Lamb wave mode must be selected. For example, on thin aluminum plate, it has been verified that the S_0 Lamb waves can give much better reflections from the through-the-thickness cracks than the A_0 Lamb waves (Giurgiutiu 2008). The selection of such a wave is achieved through the Lamb wave tuning. A wave propagation experiment was conducted on an aircraft panel to illustrate crack detection through the pulse-echo method (Figure 1). A baseline signal was first collected and then after the simulated crack was added, another reading was recorded. By comparing the difference between the reading and baseline, the reflection caused by the crack could be extracted and detected.

2.2 PWAS ACOUSTIC EMISSION DETECTION

Historically, AE signals have been captured with special-purpose AE sensors, which are costly and obtrusive. Dupont et al. (2000) studied the possibility of using embedded piezoelectric wafer sensors to detect AE signals in composite materials. To illustrate the capability of PWAS to detect AE signals in metallic structures, we performed detection experiments on the rectangular plate specimen of Figure 2a, which was already instrumented with a network of PWAS. AE events were simulated at the location P , x_P

= 400 mm, $y_p = 200$ mm. The AE events were simulated by pencil lead breaks on the specimen surface (0.5 mm HB leads). 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 2b (for display, the signals were spaced up by vertical shifts). The signal on PWAS 7, closest to the AE source ($r_7 = 71$ mm), is the strongest. This signal displays both high-frequency and low-frequency components, corresponding to S0 and A0 waves, respectively. The flexural (A0) waves display much higher amplitudes than the axial (S0) 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 pulse-echo crack detection experiment. (a) plate with built-in rivets and a simulated 12.7 mm crack; (b) baseline signal containing reflections from the plate edges and the rivets at 100 mm; (c) reading containing reflections from the crack, plate edges, and rivets; (d) subtracted signal containing reflection from crack only

Figure 2 PWAS acoustic emission detection. (a) specimen layout; (b) typical AE signals.

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

Sensor	Distance (mm)			TOF for ID (μs)
	x	y	r	
1	100	100	316	126
5	100	400	361	160
7	450	250	71	-27
9	800	100	412	185
reconstructed ID event	402.5	189.6	N/A	
actual AE/ID event	400	200	N/A	N/A

3 PWAS-BASED SENSING FOR BRIDGE HEALTH MONITORING SYSTEM

Given the massive amount of data that will be acquired by the sensing system, a major thrust of the proposed research is to develop data processing solutions to handle large quantities of data from both the active and passive interrogations. Information regarding the location and extent of damage will be used to draw qualitative conclusions regarding the current health of the structure and the scale of damage.

3.1 PWAS ADAPTATION AS AE SENSORS

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 back material (for damping the reflection from the crystal). The frequency content and sensitivity of the sensor are controlled by piezoelectric crystal and backing material. For steel structures, we adapt PWAS as AE sensors for high frequency (>150 kHz) detection where the acoustic signals propagating with minimal attenuation and minimal background noise due to the rubbing of structural components.

3.1.1 Pencil Lead Break Detection

PWAS as AE sensors were first compared with the PAC R15I on an 8-mm steel I-beam in a laboratory testing environment. The two sensors were placed face to face on the opposite surfaces of the I-beam (Figure 3). Pencil lead break was made 10-mm away from the PWAS center to simulate the acoustic emission source and the data were compared to observe any similarity in shape from these sensors. As seen in Figure 3, PWAS and R15I produced very similar relative amplitudes for the lead break emission. We also found that the amplitudes follow the predicted decay proportional to the inverse of the square root of the distance away from the sensor position, as given in Figure 4.

Figure 3 Comparison of PWAS AE sensor and R15I during a pencil lead break AE test on an 8-mm steel I-beam

Figure 4 Amplitude curves of PWAS and R15I on an 8-mm steel I-bam

3.1.2 PWAS Compact Tension Test

Compact Tension (CT) specimens, made of structural steel A572 grade 50, were used in this study. The geometry of the specimens is displayed in Figure 5a. The effective width as defined in ASTM E647 is 9.5 inches. The thickness and notch length are 0.5 inch and 3.25 inches, respectively. The cyclic tension loads of minimum 1 kN and maximum 50 kN as shown in Figure 5b 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. The surface cracks were monitored optically with a high resolution recording microscope.

Four PWAS were installed on the specimen for acoustic emission detection. For comparison, PAC R15I transducers were mounted on the opposite side of the specimen to collect AE as well. The PWAS are made of piezoceramic, 0.2-mm thick and 7-mm round (APC Inc.). They are installed on the specimen following the common procedure of strain gauge using M-200 bonding adhesive curing in room temperature. To improve the signal-to-noise ratio, PAC 2-4-6 preamplifier were used providing 40 dB amplifying factor. PWAS AE data was recorded and displayed through a 16-channel PAC Sensor Highway II-Remote Asset Integrity Monitor. The time driven rate was set at 100 ms, which permitted 10 data points to be collected in a load cycle for parametrics such as strain and load. The fixed threshold (trigger point) of each acoustic emission channel was 45 dB. Band pass analogue filter was set at 100 kHz to 1 MHz. Five waveform samples could be recorded at each μ s.

Figure 5 PWAS AE CT testing. (a) Specimen Layout; (b) tension loading cycles

Pencil lead break tests were performed before and after each loading test in order to check the performance of the transducers and to obtain reference waveforms. It was found that extraneous noise could not be completely eliminated. The AE data caused by grating of crack surfaces and extraneous noise are referred to as ‘friction emission’ in this study. Verification tests were performed to determine the intensities of the friction emission. In these tests, the maximum load in the cycles was decreased to a lower level after the crack propagated to a length of 40 mm. The lower peak load was selected so as to be insufficient to produce crack growth. All of the acoustic emission events at this lower peak load were therefore assumed to be due to friction emission. Emission having the characteristics of friction emission was then filtered by the data file filter in the Highway II monitor.

3.1.3 Results

PWAS can work as a broadband AE transducer with actual working frequency range selected by the filter band integrated in the pre-amplifiers or by the analog filter integrated in the Sensor Highway Software. 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 6. With R15I, 1171 AE events were detected before the final failure, while 54 were detected by PWAS. Figure 6a gives the cumulative acoustic energy of R15I and PWAS together with the crack opening displacement. While PWAS detect less number of acoustic activities, they detect the crack growth when the crack size reaches 0.83 mm. From Figure 6b, it can be seen that PWAS localization is more close and concentrated around the crack tip compared with the R15I detection in Figure 6c.

Figure 6 Comparison of crack localization in CT test on 1/2" steel specimen. (a) Cumulative acoustic energy by PWAS and R15I; (b) crack localization by R15I; (c) crack localization by PWAS

3.2 PWAS ACTIVE DAMAGE DETECTION

3.2.1 Sparse Array Damage Detection

PWAS sparse array consist of a network of sensors spatially distributed and are used to scan the area covered by the array. In the network, one PWAS sends out interrogating wave. When the wave encounters damage, the wave gets scattered. From the comparison of the pristine and damaged signals, a scatter signal can be extracted. By using the scatter signals from each transmission-reception pairs, an interrogation image can be constructed.

The image construction of the sparse array is based on a synthetic time reversal concept (Wang et al., 2004) by shifting back the scatter signals at time quantities defined by the transmitter-receiver locations used in the pitch-catch mode. Figure 7b and Figure 7c illustrates the imaging approach. Assuming a single damage scatter is located at point $Z(x, y)$ in the structure, the scatter signal from transmitter T_i to receiver R_j (τ_Z) contains a single wave packet caused by the damage (Figure 7c). The total time of traveling τ_Z is determined by the locations of the transmitter T_i at (x_i, y_i) , the receiver R_j at (x_j, y_j) , and $Z(x, y)$, as

$$\tau_Z = \frac{\sqrt{(x_i - x)^2 + (y_i - y)^2} + \sqrt{(x - x_j)^2 + (y - y_j)^2}}{c_g} \quad (1)$$

where c_g is the group velocity of the traveling Lamb wave, assuming constant. Using the time-reversal concept in Wang et al., 2004, when a wave packet is shifted back by the quantity defined by the transducers and the exact position of the damage, i.e., τ_Z , ideally the peak will be shifted right back to the

time origin. If the wave packet is shifted by a quantity defined with otherwise cases (such as τ_i and τ_o), the peak will not be shifted right at the time origin (Figure 7c).

For an unknown damage, for certain scatter signal with τ_Z , the possible locations of the damage is an orbit of ellipse with the transmitter and receiver as the foci (Figure 7b). To locate the damage, ellipses from other scatters (or transmitter-receiver pairs in the network) are needed. For a given network of M transducers, a total of M^2 scatter signals will be used if reciprocity is not considered. In our study, two algorithms, one based on summation process and the other based on the correlation process, have been developed for sparse array imaging. Using the summation algorithm, the pixel value at an arbitrary location $Z(x, y)$ in the scanned plane is defined as (Michaels and Michaels 2007)

$$P_Z(t_0) = \sum_{i=1}^M \sum_{j=1}^M s_{ij}(\tau_Z), i \neq j \quad (2)$$

where M is the total number of sensors in the sparse array; s_{ij} is the scatter signal obtained from i^{th} transmitter and j^{th} receiver. Using the correlation algorithm, the pixel value is defined as (Ihn and Chang 2008)

$$P_Z(t_0) = \prod_{i=1}^M \prod_{j=1}^M s_{ij}(\tau_Z), i \neq j \quad (3)$$

Figure 7 PWAS sparse array imaging principle: (a) wave scattering; (b) damage orbit; (c) signal shifting

3.2.2 Crack Detection on Thin Aluminum Plate

The sparse array imaging test was conducted on a 1-mm thick aluminum plate to detect development of a through-hole located at (328 mm, 326 mm). Four PWAS were installed on the plate at random locations to build a 4-PWAS sparse array. Scanning frequency was selected at 300 kHz to excite S0 Lamb wave mode with a traveling speed at 5500 m/s. Baseline signals were recorded when the hole had a diameter of 2 mm; then the hole was enlarged to 6 mm and measurements were taken. Imaging results using the two aforementioned algorithms are presented in Figure 8.

Figure 8 Sparse array imaging of a 1-mm aluminum plate: (a) using summation algorithm; (b) using correlation algorithm.

3.2.3 Active Sensing on CT Test

In addition to PWAS serving as AE sensors, additional PWAS were installed on the CT specimen for ultrasonic guided wave active sensing. The active sensing takes data at predetermined loading stages after crack growth is observed via AE detection. During the sensing, pitch-catch data collection is employed and processed with data analysis algorithms including damage index definition and sparse array imaging.

To obtain appropriate wave modes for damage analysis, frequency tuning was first carried out analytically and experimentally. Figure 9 gives the strain curves and dispersion curves obtained from *wavescope* software within 0-425 kHz range (Giurgiutiu 2008). It can be seen the wave excitation is very complicated on the thick plate. Experimentally, two frequencies at 138 kHz (group velocity at 3199 m/s) and 240 kHz (group velocity at 5071 m/s) have been identified where clear and/or strong arrival wave packet can be observed, as shown in figure (excitation voltage 46 volt, transmission distance 250 mm).

Figure 9 *Wavescope* tuning curves on 1/2" steel specimen. (a) group velocity; (b) strain curve.

Figure 10 PWAS frequency tuning results on 1/2" steel specimen. (a) 138 kHz; (b) 240 kHz

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.

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.

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