Steel bridge fatigue crack monitoring with broadband thin-film acoustic emission sensor

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ABSTRACT: This paper presents a fatigue crack monitoring strategy termed close range acoustic emission (AE) signal sensing enabled by the use of low-cost thin-film AE sensor. In particular, flexible piezo paint has been used to make broadband thin-film AE sensors. This close-range AE signal monitoring method offers a promising new approach to AE-induced stress-wave sensing in the ultrasonic frequency range of interest to engineering structure monitoring: low profile, conformable to curved surface, broad-band sensor that has less signal distortion in the specified frequency range, lower cost suitable for large amount use on bridges. Broadband sensing is essential to waveform based signal interpretation for identification of AE source parameters such as crack type and location. Data collected from a test-bed bridge in South Korea provides useful information for demonstrating the concept of the close-range AE signal monitoring.

1 INTRODUCTION

AE sensors based on the use of piezoelectric materials are commercially available and have seen growing use in fatigue crack monitoring in metallic structures. Recently, piezoelectric composites have received considerable interest as sensing elements because of their favorable material properties that often cannot be obtained in single-phase materials. Polymer-based piezo paint is comprised of tiny piezoelectric ceramic particles randomly dispersed within a polymer matrix. Therefore, through judicious selection of the polymer matrix, the composite properties of piezo paint can be tailored to meet the requirements of specific application conditions. For example, piezo paint might be more suitable for use on curved surfaces, such as steel bridge fatigue crack monitoring, because of its flexibility and low-profile configuration. Piezo paint AE sensor developed by Zhang (2006), Zhang & Li (2006,2008), Li and Zhang (2008) in recent years focuses on applications involving the detection of fatigue cracks in metallic structures with complex geometries, especially in the high-stress areas with geometric discontinuity where defect often first initiates. In particular, flexible piezo paint has been used to make broadband thin-film AE sensors. Compared with conventional AE sensors used today, which is based on a 2nd-order dynamic oscillator operating principle measuring displacement perpendicular to the monitoring surface, thin-film AE sensor measures stress-wave-induced in-plane strain which is based on a zero-order sensing principle. Placing such AE sensors close to potential AE source (e.g., crack) locations makes the relatively low cost, near-field AE signal monitoring possible, although strain-measurement-based zero-order AE sensor would have a lower sensitivity compared to the commonly used displacement-measurement-based second-order AE sensors presently. This close-range AE signal monitoring method offers a promising new approach to AE-induced stress-wave sensing in the ultrasonic frequency range of interest to engineering structure monitoring: low profile, conformable to curved surface, broadband sensor that has less signal distortion in the specified frequency range, lower cost suitable for large amount use on bridges. Broadband sensing is essential to waveform based signal interpretation for identification of AE source parameters such as crack type and location.

2 STRAIN-BASED AE SENSOR

2.1 *Strain-based AE sensor for near field monitoring*

Near field AE monitoring strategy with thin-film AE sensor is different from traditional monitoring strategies, such as strain gage monitoring, or displacement sensor monitoring. Although the thin-film sensor works based on strain measurement, the sensitivity of this thin-film sensor is much higher than normal strain gauges. It operates in ultrasonic frequency range, which make itself could response to rapid stress release in nearby locations such as fatigue crack propagation. These burst signals could be easily missed by conventional strain gauges. Another feature of near field monitoring is its lower sensitivity compared with displacement sensor leading to environmental load-induced noise immunity. The near field monitoring strategy is designed to mainly watch the locations it takes care of. Environmental load-induced noise is not of interest. Thus it could be easier to locate where the AE source coming from. The most important thing for near field monitoring is its ability to perform inverse analysis. For traditional AE displacement sensors, due to the high cost, each sensor usually takes a larger area. In civil structures, there are many possible AE sources and the wave propagation in the structure is also very complicated. The strain-based AE sensor, due to its lower cost, each one could be focused on a relative smaller area compared with the displacement sensor. Although the strain-based AE sensors usually have much lower sensitivity than displacement sensor, its smaller monitoring areas could make up this disadvantage. Additionally, as strain-based AE sensors are set near the potential AE source as close as possible, complexity in wave propagation analysis is greatly reduced.

Since the displacement based sensors have been used a lot, many studies have been conducted for displacement based sensors (Proctor, 1982, Ohtsu & Ono, 1984, Yuyama et al. 1987, Fortunko et al. 1992, Ohtsu, 1995). Generalized AE theory for waveform based signal analysis has also been proposed for displacement-based AE sensing (Ohtsu & Ono, 1984). However, little researches have been done for strain-measurement-based AE sensing. Although the feasibility of using strain sensor for AE sensing has been demonstrated by Li and Zhang (2008), some more work are necessary, including a similar generalized theory for waveform based analysis as well as the characterization and calibration of such AE sensors for using in near field monitoring applications.

2.2 *Waveform based signal analysis for strain-based AE sensor*

There are two basic methods in AE signal analysis: waveform based analysis and parameter based analysis. For waveform based technique, a broadband AE sensor is needed to acquire the signal, which is just one of piezo paint AE sensor's advantages. Waveform based technique usually needs to synthesize AE waveforms due to crack initiation and then compare with the obtained signals. Moment tensor analysis can be used for synthesizing AE waves due to crack initiation. It has been used in seismology field for quite some time and is recently receiving more attention in AE signal analysis. In moment tensor analysis, moment tensors (dipoles or double couples) weighted Greens' functions are employed to represent the synthetic waveform. According to the generalized AE theory (Ohtsu & Ono, 1984), signals initiating from hidden fatigue crack can be expressed as,

$$u_k(x,t) = G_{kp,q}(x,y,t) * S(t) M_{pq} \qquad (1)$$

Where u_k is the displacement in direction k; C_{pqij} are elastic constants; M_{pq} is the moment tensor component; $G_{kp,q}$ is the spatial derivative of the Green's function G_{kp} with respect to coordinate q. With different combinations of moment tensors and Green's functions, different cracking modes can be represented with Equation 1.

Since the output voltage of piezo paint AE sensor is proportional to the integral of the in-plane strain if a charge amplifier is used (Li, 2009), thus the strain ε_k need to be obtained for using strain-based AE sensor which is shown in Equation 2. With the expressions in Equation 2, the resulted strain could be easily formulated for different geometries and cracking modes.

$$\begin{aligned}
\varepsilon_k(\mathbf{x},t;\mathbf{x}',t') &= \lim_{\Delta x_k \to 0} \frac{u_k(\mathbf{x}+\Delta\mathbf{x}_k,t;\mathbf{x}',t') - u_k(\mathbf{x},t;\mathbf{x}',t')}{\Delta x_k} \\
&= \lim_{\Delta x_k \to 0} \frac{G_{kp,q'}(\mathbf{x}+\Delta\mathbf{x}_k,t;\mathbf{x}',t') - G_{kp,q'}(\mathbf{x},t;\mathbf{x}',t')}{\Delta x_k} * S(t) M_{pq} \\
&= G_{kp,q'k}(\mathbf{x},t;\mathbf{x}',t') * S(t) M_{pq}
\end{aligned} \qquad (2)$$

2.3 *Strain AE signal due to surface pulse*

Surface pulse is a popular AE source in studying AE sensor characteristics. The Raleigh wave generate by surface pulse usually contains broad band contents, which is suitable for sensor calibration. The calculation of wave propagation due to surface pulse is also easier compared to buried pulse since the source can be well controlled. Thanks to these characteristics, studying sensor response to a surface step force has been a standard procedure for AE displacement sensor calibration (ASTM E1106). Although there is no widely accepted calibration procedure for strain measurement type sensors operating in ultrasonic range so far, knowing the response of a strain-based AE sensor to such surface step force would help understand the working principle of strain-based AE sensor in quantity. The calculation of surface displacement due to a surface step force on a half space has been studied, while it seems no existing formula to calculate the strain response. It can be shown that the surface in plane strain due to a surface pulse on a half space could be derived as follows,

$$\varepsilon(t)=\frac{1}{\pi\mu r}\begin{cases} 0 & \text{for T} < 1 \\ \frac{\partial^2}{\partial t^2}\left\{\frac{2T^2A}{\pi\alpha}\int_0^{\pi/2}\frac{(P^2-1)(A-P^2)^{1/2}(A-2P^2)}{(A-2P^2)^4-16X^2Y^2P^4}d\chi\right\} & \text{for} 1 < T < \alpha/\beta \\ \frac{\partial^2}{\partial t^2}\left\{\frac{2T^2A}{\pi\alpha}\int_0^{\pi/2}\frac{(P^2-1)(A-P^2)\ (A-2P^2)}{(T^2-P^2)^{1/2}[(A-2P^2)^4-16X^2Y^2P^4]}d\chi-\frac{H(T-R_3^{1/2})T^2c_8}{\alpha(T^2-R_3)^{1/2}}\right\} & \text{for} \alpha/\beta < T \end{cases} \tag{3}$$

Where in the Equation 3, μ is shear modulus; r here is the distance from source to sensor; α is the P wave speed and β is the S wave speed; $A = (\alpha/\beta)^2$; T is the normalized time, which equals ($\alpha t/r$), and

$$X=(1-P^2)^{1/2} \quad \text{or} \quad -i(P^2-1)^{1/2} \tag{4}$$

$$Y=(A-P^2)^{1/2} \quad \text{or} \quad -i(P^2-A)^{1/2} \tag{5}$$

When $1<T<\alpha/\beta$

$$P^2=(T^2-1)\sin^2\chi+1 \tag{6}$$

While when $\alpha/\beta< T$

$$P^2=(A-1)\sin^2\chi+1 \tag{7}$$

Second part in Equation 3 when $\alpha/\beta< T$ results from the residual of complex integral at the pole of the integrand (Richards, P. G., 1979). And the parameters are

$$\begin{aligned} c_8 &= \frac{1}{2}cA(A-2R_3)^3/R_3 \\ c &= 1/[16(A-1)(R_3-R_1)(R_2-R_3)] \end{aligned} \tag{8}$$

R_3 is the largest root of the Raleigh cubic which is always real; R_1 and R_2 are the other two roots of the Raleigh cubic which are real if Poisson's ratio is smaller than 0.263 and two complex conjugates when Poisson's ratio is larger than 0.263(Richards, P. G., 1979).

Based on the derived formula for pulse source, the waveform for other type sources can also be obtained. In Figure 1, it shows the strain - based sensor response due to a force of time history $S(t)$, where

$$dS(t)/dt=\sin^4(\pi t/T_r), \quad (0<t<T_r) \tag{9}$$

and T_r is the rise time, which is set to be 2 µs. This kind of source time function is also adopted by other researchers in fatigue study (Ohtsu, 1995).The strain- based AE sensor has a circular aperture with a diameter of 1/2" and waveform shown in Figure 1 already considers the aperture effect. It can be seen that the strain-based AE sensor response is different from a regular displacement sensor response. Under an approximate step force, the strain response is more like a vibration signal.

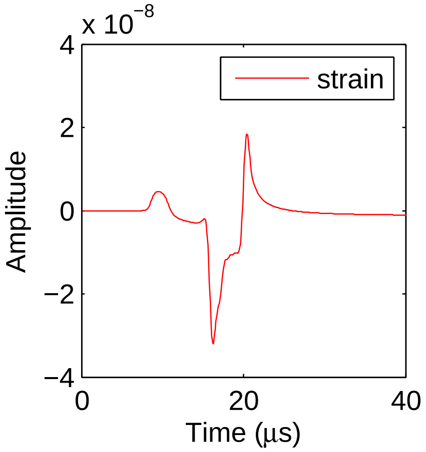


Figure 1. Theoretical waveform due to a surface force on a half space with source function S(t) at 2 inches distance with aperture effect.

3 EXPERIMENTAL VERIFICATION OF STRAIN-BASED AE SENSOR

3.1 AE Strain signal due to surface pulse

Step force on the surface of half space is a popular AE source in experiment. The pencil lead break and breaking glass capillary are good candidates for such kind of surface AE source with an approximate step force. In this paper, breaking glass capillary will be used to simulate the surface AE force. In Figure 2, it shows the experimental set up. In this experiment, a steel block with a dimension of 20"×20"×4"is used to simulate the half space medium, while the glass capillary breaking is used to simulate the AE source generating a step force. A strain-based AE sensor made from piezo paint is mounted on the steel surface with conductive epoxy. This sensor is circular and has a diameter of 1/2". It is connected to a 40dB amplifier and a filter with a pass band of 5-600 kHz. A commercial flat response sensor (SE 1000-H) from Dunegan Engineering Company, Inc. is placed symmetric to the strain-based AE sensor made from piezo paint. The SE 1000-H has a 20dB amplifier. The source lies in the middle of the two sensors - 1.5" away from each.

In Figure 3 (a) and (b), it shows the waveforms acquired by the two sensors separately as well as the corresponding frequency response. The P wave (first wave arrival) and Raleigh wave (largest wave arrival) arrivals match very well with each other. The response of SE 1000-H shown in Figure 3 (a) meets the expectation of a waveform due to a breaking glass capillary, which is commonly recognized. The strain-based AE sensor behaves very well under 600 kHz. Starting from 600 kHz, the frequency response begins to roll down. This is because of the cut off frequency of this strain sensor is set to be 600 kHz. It is evident that strain-based AE sensor has comparable performance with the commercial AE displacement sensor after signal conditioning. It also can be seen that the frequency response of this strain-based AE sensor made from piezo paint is relatively flat, which matches the sensing material characteristics analyzed by impedance (Zhang, et al. 2009).

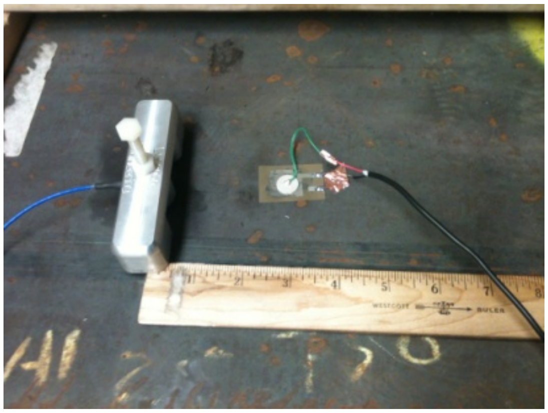
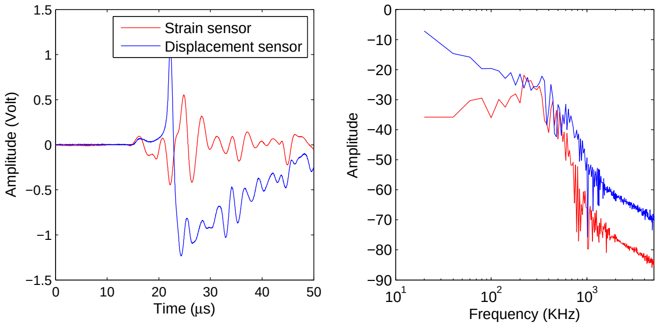


Figure 2. Surface pulse test set up



(a) (b)

Figure 3. Sensor response of surface pulse: (a) response in time history; (b) frequency spectrum

3.2 A thin-film sensor test on bridge

In October, 2010, field test of this strain-based AE sensor was conducted on a steel I-girder bridge near Icheon, South Korea. A portable steel plate with a preloaded fatigue crack was attached to the mid-span of this bridge. Four strain-based AE sensors with a diameter of 1/2" were mounted on the pre-cracked steel plate as shown in Figure 4. Sensors were connected to a 40 dB preamplifier and a band pass filter with a pass band of 5 kHz-600 kHz. A truck with 25-ton gross vehicle weight (GVW) crossed the bridge at different speeds to simulate AE signals generated by traffic. Since the bridge was closed to traffic at the time of test, the only possible AE source was from the truck's pass, which was under control. The controllable traffic load could make it easier to study the effect of environmental induced load for near field monitoring, so that the near field monitoring could be designed to be noise immune. This experiment was also designed to conduct the waveform based signal analysis through the acquired AE signals emitting from the opening of the existing fatigue crack on the attached steel plate, although no cracking induced AE signal was seen during the experiment.

Figure 4. Steel plate with four sensors mounted on the lower flange of the I-girder bridge

Figure 5 shows one sample signal from one of the four sensors as well as its corresponding frequency spectrum when the truck passed the bridge at a speed of 80km/h. As one can see, after amplification and filtering, the strain-based AE sensor could get rather clear signal. It should be noted that the strain-based AE sensors didn't response when the truck passed at speeds of 10km/h and 30km/h. Only the 80 km/h truck passed by could excite the strain-based AE sensor response while the displacement sensor always responded with a very large magnitude (larger than 1 volt). This kind of insensitivity reveals the noise immunity property of thin-film sensor in near filed monitoring for low speed traffic. Waveform in Figure 5 has a relative low amplitude. The frequency contents are also mainly below 10 kHz, while the fatigues signal usually falls in the range of several hundred kHz. It is possible to have a sensor designed to be such environmental load immune. In this test, the sensors were only put on to monitor the attached steel plate area. It can be seen that the geometry is a plate. The Green's function in reverse analysis as specified in section 2.2 is much easier compared with other complex details on bridge. Accordingly, the inverse analysis is able to perform.

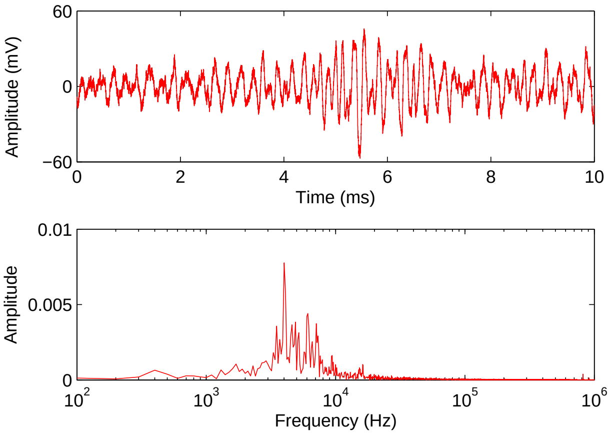


Figure 5. Vehicle induced AE signal

4 CONCLUSION

Strain-based thin-film AE sensor offers a new tool that enables close-range AE signal monitoring. With a number of advantages, it is very promising for fatigue crack monitoring.

In this study, the surface pulse response of strain - based thin-film AE sensors has been studied both analytically and experimentally. For the analytical part, the derived formula could be used for calibration purpose or sensor design based on numerical simulations in the future. In the experiments involving the glass capillary breaking test, comparable performance with the displacement sensor was observed for the strain-based thin-film AE sensor using piezoelectric paint dots. The piezoelectric paint sensor exhibits a relatively broadband frequency response, which makes low-cost, broadband AE signal monitoring possible. An experimental test conducted on a steel highway bridge also demonstrates one aspect of the close-range AE monitoring, i.e., immunity to environmental noise.

Future work for the strain-based AE sensor will be focused on real fatigue crack source based on lab and field test on real bridge components.

5 ACKNOWLEDGEMENT

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