6th European Workshop on
Structural Health Monitoring - Poster 21

Acoustic Emission Source Localization on Concrete Structures with Focusing Array Imaging

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ABSTRACT

Passive piezoelectric sensing, also known as acoustic emission (AE) monitoring, detects and locates cracks within the concrete when the formation of a crack or corrosion generates a stress wave that causes the sensor to become excited. The extreme sensitivity of AE testing makes it a promising approach for structural monitoring because cracks do not need to be visible and the sensors only need to be located in the general vicinity of active cracking (within a 10 foot radius) to detect and record the event. Locations of cracks can be found by time-based waveform analysis.

In this paper, we will present a novel acoustic emission array imaging algorithm that detect and locate the AE source by back propagating the received AE signals. The method uses solids waves and requires only a small array of 4 to 8 sensors. The beamforming array geometry will allow the normal AE passive mode and be used for imaging as an additional signal processing tool. Eventually, beamforming AE can reduce sampling rate and time synchronization requirements between spatially distant sensors which in turn facilitate the use of wireless sensor networks for this application. The beamforming method is promising and economically beneficial for solving a key source localization problem in damage detection on large concrete structures.

KEYWORDS

Acoustic Emission, array imaging, focusing array, concrete, piezoelectric wafer sensors

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INTRODUCTION

The rapid deterioration of civil structures, such as bridges, is a cause of major concern all over the world. Safely extending the life while maximizing load carrying capabilities of those bridges and maintaining uninterrupted traffic operations is of great importance and economic benefits to the infrastructure owners. Achieving such goals depends to a large extent on developing and maintaining an effective inspection routine. In the past, monitoring of structures was usually done by means of visual inspection and tapping of the structures using a small hammer (Tan et al., 2009). Recent advancements of sensors and information technologies have resulted in new ways of structural health monitoring the performance and deterioration. Structural health monitoring (SHM) refers to the procedure used to assess the condition of structures so that their performance can be monitored at any time and damage can be detected at its early stage, thus increasing reliability, safety and efficiency of the structures. The process of SHM typically involves monitoring of a structure over long period of time using permanently installed sensors, data interpretation algorithms to extract damage related information from the sensory measurements, and analysis of the damage extent in order to determine the current state of the structure.

Active or growing flaw such as cracking and corrosion emits acoustic emission (AE) waves under load. AE waves are stress waves that arise from the rapid release of strain energy that follows micro structural changes in a material (Vahaviolos, 1996). The AE technology has been widely used in various mechanical engineering applications and for monitoring concrete constructions such as power plants and bridges (Miller and McIntire, 1987) (Nair, 2006). AE waves can be recorded by means of sensors placed on the surface of a structure. The sensors are constructed with piezoelectric materials which convert mechanical motions to electrical signals. Analysis of these recorded signals provides information about the source of the AE with very high sensitivity. Evaluation of the detected AE waves gives an overall picture about the condition of the concrete structures and helps to prioritize repair and maintenance. It is classified as passive structural health monitoring techniques and can be used for real time monitoring (Tan et al., 2009). Another dominant attribute of AE technique is its capability to detect a failure at a very early stage, long before a structure completely fails. Compared to other commonly used nondestructive evaluation (NDE) technologies such as ultrasonic inspection, AE was one of the very few techniques with both global and local monitoring capabilities (Maji et al., 1997).

In this paper, the authors will present a novel algorithm for AE localization on concrete structures using the wave-scattering based array imaging approach. Ultrasonic waves in solids have been widely used for SHM and NDE since they interact sensitively with small defects with comparable sizes to the wave lengths. The waves can be excited (for active mode) or measured (for passive mode) by surface mounted piezoelectric transducers and processed for diagnostic purposes. In the last decade, imaging approaches for damage localization have been developed using pitch-catch method to evaluate the wave propagation between the source and the sensors in all possible paths in a sensor network (Ihn and Chang, 2008; Michaels and Michaels, 2007; Yu and Giurgiutiu, 2010). The methods determine damage probability or intensity at discrete points on the structure that leads to an image where the highest intensity represents the damage position.

EXPERIMENTAL TESTING

Piezoelectric Wafer Active Sensors

PWAS operate on the piezoelectric principles that couple the mechanical and electrical properties of the material. PWAS 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 they can be used as both actuators and sensors. The coupling between the electrical and the mechanical variables (the charge per unit stress and the strain per unit electric field) is signified by the coefficients d_{ij} (i=1,…,6; j=1,2,3), also known as the polarization coefficient. In practical applications, many of the piezoelectric coefficients d_{ij} have negligible values as the piezoelectric materials respond preferentially along certain directions depending on their intrinsic (spontaneous) polarization. For PWAS depicted in Figure 1, assume that the applied electric field E_3 is parallel to the spontaneous polarization Ps, with Ps aligned with the x_3 axis. E_3 can be created through the application of a voltage V between the top and bottom electrode of the wafer represented by the shading. The application of $E_3//P_s$ results in a vertical (thickness wise) expansion $\varepsilon_3=d_{33}E_3$ and a lateral (in plane) contractions $\varepsilon_1=d_{31}E_3$ and $\varepsilon_2=d_{32}E_3$ (the lateral strains are contracted as the coefficient d_{31} and d_{32} have opposite sign to d_{33}). The strains experienced by PWAS are direct strains. Such an arrangement can be used to produce thickness-wise and in-plane vibration of the wafer. In elastic wave generation and sensing, PWAS couple their in-plane motion with the particle motion of waves on the material surface, which is excited by the applied oscillatory voltage through the d_{31} piezoelectric coupling (Giurgiutiu, 2008).

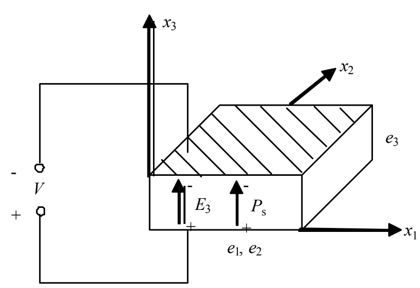

Figure 1. elastic wave generation and reception, the induced-strain responses.

Test Setup on a Concrete Beam

A preliminary study of sensing and detection using Rayleigh waves in a bulky concrete beam has been conducted. The test specimen is a 6”×6”×30” beam (E = 2.49 MPa, ρ=2400 kg/m^3, ν=0.2). Square APC-850* PWAS (E_a = 63 GPa, t_a = 0.2 mm, l_a = 7 mm, d_{31} = - 175 mm/kV) are bonded to one surface of the beam, as shown in Figure 2. The bonding layer modulus is assumed ideal with G_b = 2GPa. The data

* APC International Inc. http://www.americanpiezo.com/apc-materials/choosing.html

acquisition is conducted by a digital oscilloscope. In active interrogation, a function generator can be used to send out the excitation.

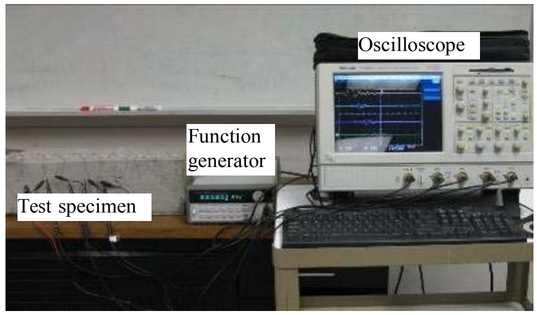

Figure 2. Laboratory setup on surface wave excitation and sensing using PWAS.

Surface Rayleigh Waves Excitation and Sensing

The propagation of stress waves through a heterogeneous medium such as concrete is a very complex phenomenon. As waves propagate through a solid concrete medium, the energy is scattered away from the original wave path. Rapid attenuation of the signal occurs when the amount of signal scattering is intensified, that is, when the wavelength of the propagating wave coincides in size or is smaller than the size of the internal discontinuity or internal flaw that is causing the wave scattering. In addition, the inherent inhomogeneity of concrete causes a large amount of backscattering (deflection of incoming waves from their original direction) of the longitudinal waves, which leads to signal noise and a decrease in the ability to detect the particle motion travelling parallel to the propagating waves.

Researchers have tried to apply ultrasonic waves with frequencies in the range from 40 to 200 kHz producing a wavelength of pressure waves in concrete between approximately 100 mm to 20 mm. The use of long wavelengths in the pulse-echo technique is effective for the detection of internal objects, but a strong backscatter of the incident pulse may occur. The signals from the internal objects to be detected might be masked from this structural noise.

One PWAS was used as a transmitter to send out a toneburst made of a 3-count sin signal smoothed by Hanning window with a center frequency of 150 kHz to excite surface waves in the beam. Another PWAS about 300 mm away was used as a sensor to receive the propagation waves. The measurement is shown in Figure 3 (left). P-wave travels quicker but with much smaller amplitude while Rayleigh wave travels slower with strong strength. It is evidenced that PWAS can excite high quality high frequency Rayleigh waves well above 100 kHz. The Rayleigh wave field is shown in Figure 3 (right) to shown the wave interaction with PWAS and propagation down through the thickness.

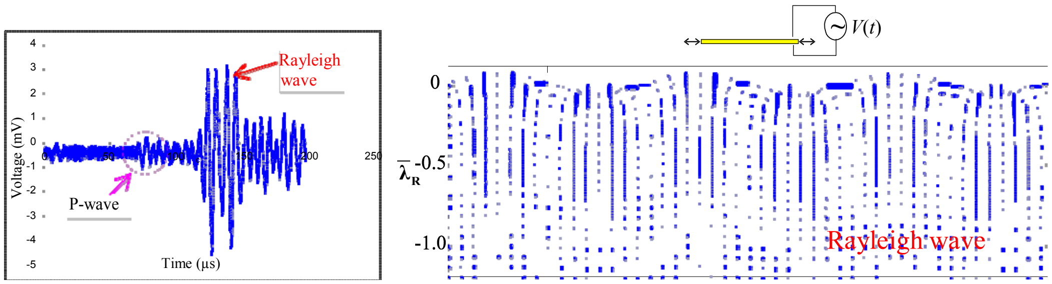

Figure 3. Typical Rayleigh surface wave excited by surface mounted PWAS (left) and its interaction with surface mounted PWAS (right).

FOCUSING ARRAY IMAGING ALGORITHM

A major challenge of current sensor-based ultrasonic wave health monitoring methodologies is to quantify the damage based on sensor measurements. Although advances in ultrasonic based SHM have demonstrated its feasibility of detecting the presence of damage in concrete materials, quantitatively evaluating the damage based on sensory data remains a challenging task. Without quantitative information of the damage, meaningful prediction of remaining life or residual strength of damaged structures is not possible. When multiple sensors are used, imaging algorithms are a useful way of fusing data obtained from each sensor, thus improving the reliability of the detection results and providing the capability of damage localization.

The focusing array imaging uses the scattering signals from damage source assuming that a flaw is the only change that has occurred. That's to say, the signals only contain waves scattering from the flaw. The approach also assumes that only a single guided wave mode is analyzed such that the group velocity of the mode can be calculated from the time of the direct arrival and the time of a scattered signal from a flaw at a specific location. The imaging array consists of a network of PWAS spatially distributed along the structures that receive the wave scattered from the flaw or source simultaneously. The imaging algorithm then process all collected scattering signals from the sensors to construct an intensity image to indicate the location of the source. This methodology is an alternative to conventional NDE and can most likely be implemented without disassembly of the structure for many applications.

The image construction algorithm is based on the synthetic time reversal concept originally used in active sensing by shifting back time difference signals to their time origin (Wang et al., 2004). Figure 4 illustrates the imaging concept. Assume that a single scattering source is located at point $Z(x, y)$ in the structure. When activated, a wave propagates outward to all directions from the source and will be recorded by the spatially distributed array network. In the measurement, the time of arrival τ_Z is determined by the locations of the source $Z(x, y)$ and the sensor R_i at (x_i, y_i):

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

where c_g is the group velocity of the traveling wave, assuming constant.

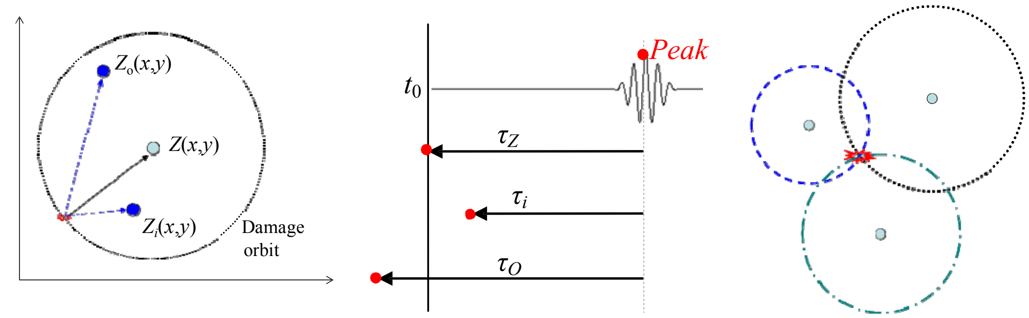

Figure 4. Focusing array algorithm for passive AE imaging, the orbit for possible damage location (left), the back propagation (middle), and the triangulation principle for pinpointing the AE source location (right).

Using the time-reversal concept, 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 4). For an unknown damage source with τ_Z, the possible locations of the damage are on the orbit of a circle with the source at the origin and source-sensor distance as the radius. To pinpoint the damage, orbits from other source-sensor pairs in the array are needed. For a given array of M transducers, a total of M scatter signals can be used and need to be fused together to obtain damage detection results. In our study, two algorithms, an OR fusing algorithm using OR logical operation and an AND fusing algorithm using AND logical operation, have been employed for the imaging, defined as

AND $$P_Z\left(t_0\right)=\sum_{i=1}^{M} s_i(\tau_Z) \qquad (2)$$

OR $$P_Z\left(t_0\right)=\prod_{i=1}^{M} s_i(\tau_Z) \qquad (3)$$

where $s_i()$ is the signal energy after time reversal received at i^{th} sensor. P_Z is the pixel value calculated for the location $Z(x, y)$. The OR algorithm is different from the AND algorithm since when and only when all sensors identify location $Z(x, y)$ is a damage location, it is, similar to the logical operation in Boolean algebra.

In most of the cases, minimum three sensors are needed for the detection of the source location (Figure 4, right). When the source falls in between the sensors, to ensure localization precision, minimum four sensors are suggested to use.

RESULTS

In the proof-of-concept test, the AE source is simulated by exciting a 7-mm square PWAS (APC850*) using a 150 kHz 3 count toneburst to generate Rayleigh surface wave. The source location is (70, 50) (unit: mm) in the coordinates. An array of sensors has been installed on the surface of the beam as shown in Figure 5. Receivers 1, 3, 5, 11

* http://www.americanpiezo.com/apc-materials/choosing.html

are selected to form a focusing array to verify the imaging algorithm developed in previous section. The positions are (0, 80), (30, 0), (110, 0) and (140, 100), respectively (unit: mm). Wave velocity of the Rayleigh wave is found to be 1894 m/s according to

$$C_R = \frac{0.87 + 1.12\nu}{1+\nu} C_S \text{ and } C_S = \sqrt{\frac{E}{2\rho(1+\nu)}} \tag{4}$$

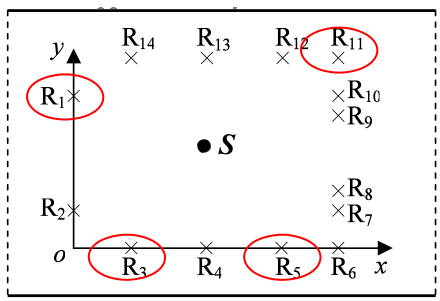

Figure 5. AE array imaging layout.

Imaging results using the four-PWAS array are shown in Figure 6 for OR and AND algorithms, respectively. The centers of the highlighted area are both about (69, 50) (unit: mm), very precise detection being achieved. It can be seen from the comparison of the two algorithms that the OR algorithm provide the maximum possibility of damage occurrence on the structure while the AND algorithm only provide the possibility if and only if all the sensors confirm that the location is a defect site. Despite of the better resolution, AND algorithm has the shortcoming of low error tolerance. If a mis-locating were conducted by a sensor, the entire detection would be invalid.

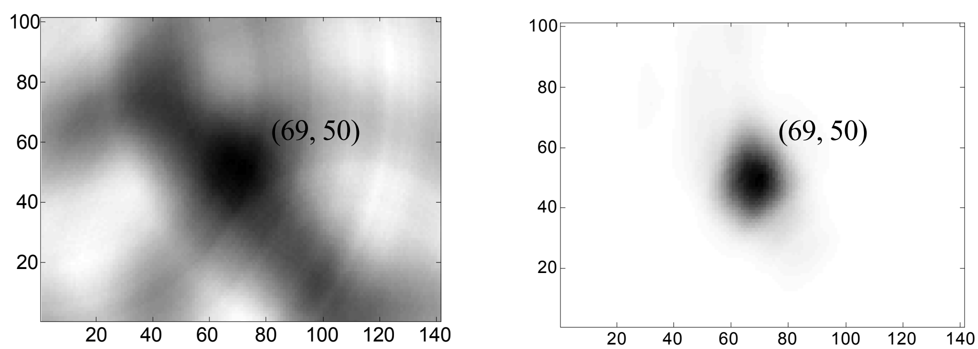

Figure 6. AE array imaging of simulated source results using OR (left) and ANR (right) algorithms.

CONCLUSIONS

In this paper, a passive acoustic emission imaging approach using piezoelectric wafer active sensor focusing array algorithm was presented. The imaging approach was applied to a concrete beam to detect a simulated acoustic source using Rayleigh waves and has obtained good results. The focusing array uses the scattering signals, having the advantages of using a minimum of three to four sensors and being able to image the entire specimen. The resolution can be improved with use of more sensors. The next step of the work will be using the focusing array to detect more realistic acoustic emission.

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