International Journal of Advanced Research in

Electronics, Communication & Instrumentation Engineering and Development

Volume: 2 Issue: 3 26-Dec-2014,ISSN_NO: 2347 -7210

Structural Health Monitoring and Wireless Damage Detection with Piezoelectric Wafer Active Sensors

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ABSTRACT— *In this paper we review the state of the art in an emerging new technology: embedded ultrasonic non-destructive evaluation (NDE). Embedded ultrasonic NDE permits active structural health monitoring, i.e. the on-demand interrogation of the structure to determine its current state of structural health. The enabling element of embedded ultrasonic NDE is the piezoelectric wafer active sensor (PWAS). Piezoelectric wafer active sensors (PWAS) are lightweight and inexpensive enablers for a large class of structural health monitoring (SHM) and damage detection applications. PWAS are multi-mode, i.e., they can be used for damage detection using both active and passive methods and utilizing both traveling guided waves (acousto-ultrasonics) as well as standing waves (vibration) techniques. PWAS have several applications in the areas of: (a) embedded guided-wave ultrasonics, e.g., pulse-echo and phased arrays; (b) high-frequency modal sensing, i.e., the electro-mechanical (E/M) impedance method. The paper ends with conclusions and suggestions for further work.*

Keywords: Structural health monitoring; SHM; piezoelectric wafer active sensors; PWAS; electromechanical impedance; EMIS; acousto-ultrasonics; guided waves; Lamb waves;

1, INTRODUCTION *(SHM)*

Structural health monitoring (SHM) is an emerging technology with multiple applications in the evaluation of critical structures. The goal of SHM research is to develop a monitoring methodology that is capable of detecting and identifying, with minimal human intervention, various damage types during the service life of the structure. SHM assesses the state of structural health and, through appropriate data processing and interpretation, predicts the remaining life of the structure. Numerous approaches have been utilized in recent years to perform structural health monitoring [1,2]; they can be broadly classified into two categories: (a) passive SHM methods and (b) active SHM methods. Passive SHM methods (such as acoustic emission, impact detection, strain measurement, etc.) have been studied longer and are relatively mature; however, they suffer from several drawbacks which limit their utility (need for continuous monitoring, indirect inference of damage existence, etc.). Active SHM methods are of greater interest due to their ability to perform on-demand interrogation of a structure while the structure is still in service. One of the promising active SHM methods utilizes arrays of piezoelectric wafer active sensors (PWAS) bonded to a structure for both transmitting and receiving ultrasonic waves in order to achieve damage detection [3]. When used to interrogate thin-wall structures, the PWAS are effective guided wave transducers which couple their in-plane motion with the guided wave particle motion on the material surface. The in-plane PWAS motion is excited by an applied high-frequency voltage through the piezoelectric effect. Optimum excitation and detection takes place when the PWAS length is in certain ratios with the wavelength of the guided wave modes.

2, BACKGROUND AND MOTIVATION

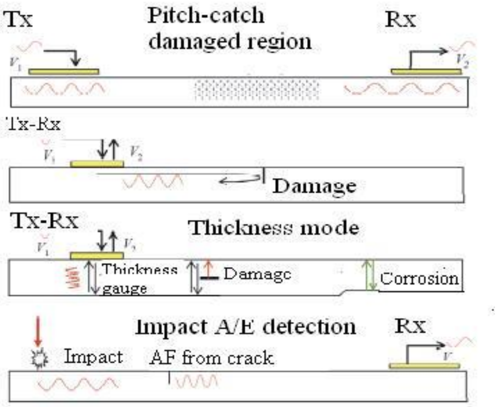
However, PWAS are different from conventional ultrasonic transducers in several aspects:

1. PWAS are firmly coupled with the structure through an adhesive bonding, whereas conventional ultrasonic transducers are weakly coupled through gel, water, or air.
2. PWAS are non-resonant devices that can be tuned into several guided-wave modes, whereas conventional ultrasonic transducers are resonant narrow-band devices.
3. PWAS are inexpensive and can be deployed in large numbers on the structure, whereas conventional ultrasonic transducers are expensive and hence less likely to be deployed in as large a number as the PWAS transducers.

By using Lamb waves in a thin-wall structure, one can detect structural anomaly, i.e., cracks, corrosions, delaminations, and other damage. Because of the physical, mechanical, and piezoelectric properties of PWAS transducers, they act as both transmitters and receivers of Lamb waves traveling through the structure. Upon excitation with an electric signal, the PWAS generate Lamb waves which travel through the thin-wall structure and are reflected or diffracted by the structural boundaries, discontinuities, and damage. The reflected or diffracted waves arrive at the receiver PWAS transducers where they are transformed into electric signals.

PWAS transducers can serve several purposes [3,4,5,6]: (a) high-bandwidth strain sensors; (b) high-bandwidth wave exciters and receivers; (c) resonators; (d) embedded modal sensors using the electromechanical (E/M) impedance method. The PWAS transducers have various modes of operation (Figure 1): (i) far-field active sensing using pulse-echo, pitch-catch, and phased-array methods, (ii) near-field active sensing using high-frequency E/M impedance method and thickness-gage mode, and (iii) passive sensing of damage-generating events through detection of low-velocity impacts and acoustic emission at the advancing crack tip. Damage detection using PWAS phased arrays can detect several cracks independently with scanning beam emitted from a central location.

Modes of operation of PWAS Transducers



elements aligned at uniform 9-mm pitch. The PWAS phased array was placed at the center of a 4-ft square thin aluminum plate (Figure 2a).

The wave pattern generated by the phased array is the result of the superposition of the waves generated by each individual element. By sequentially firing the individual elements of an array transducer at slightly different times, the ultrasonic wave front can be focused or steered in a specific direction. Thus, electronic sweeping and/or refocusing of the beam without physical manipulating the transducers is achieved. inspection of a wide zone is possible by creating a sweeping beam of ultrasonic Lamb waves that covered the whole plate. Once the beam steering and focusing was established, the detection of crack was done with the pulse-echo method. The EUSR methodology was used to detect cracks in two typical situations: (i) a 19-mm broadside crack placed at

305 mm from the array in the 90 deg direction; and (ii) a 19-mm broadside crack placed at 409 mm from the array in the 136 deg direction. Figure 2b presents the front panel of the embedded ultrasonic structural radar graphical user interface (EUSR-GUI) displaying the offside signals

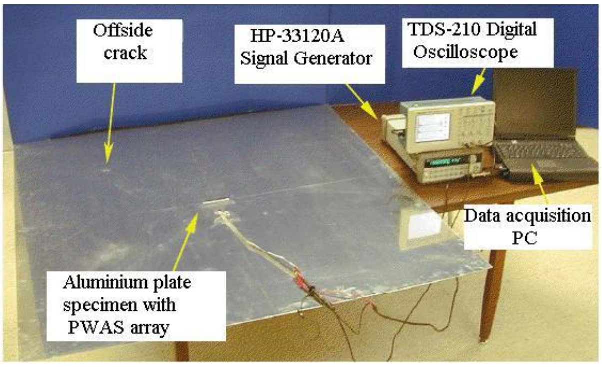
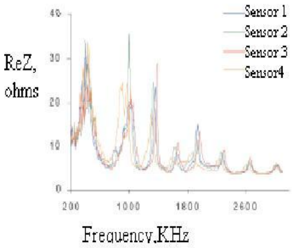


Figure 1a- Propagating guided Lamb Waves



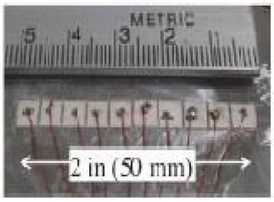


Figure 1b – Standing guided Lamb Figure 1c- PWAS Phased Arrays Waves(E/M Impedence)

3, PWAS PHASED ARRAYS

The phased array ultrasonic transducers have been developed in conventional ultrasonic NDE for the inspection of very thick specimens, the sidewise inspection of thick slabs, etc.[7]. These transducers employ pressure waves generated through normal impingement on the material surface. we have developed a phased array technology for thin wall structures (e.g., aircraft shells, storage tanks, large pipes, etc.) that uses guided Lamb waves to cover a large surface area through beam steering from a central location. We called this concept *embedded ultrasonics structural radar* (EUSR). A PWAS array was made up of a number of identical 7-mm sq.

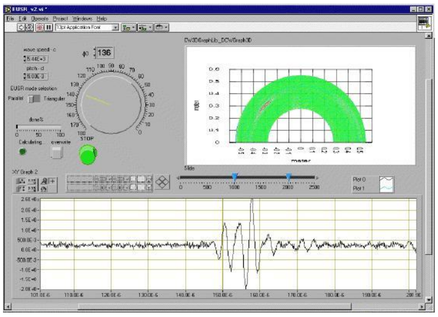


Figure 2a-Proof-of-concept EUSR experiment: thin palte specimen 9-element PWAS array and 19 mm offside crack.

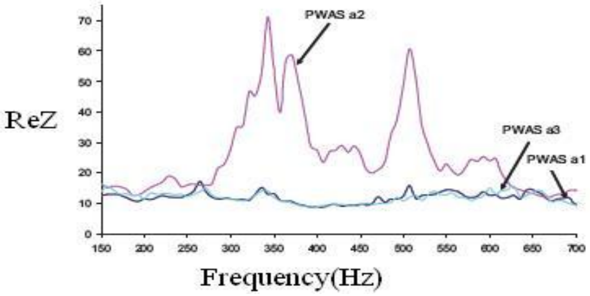
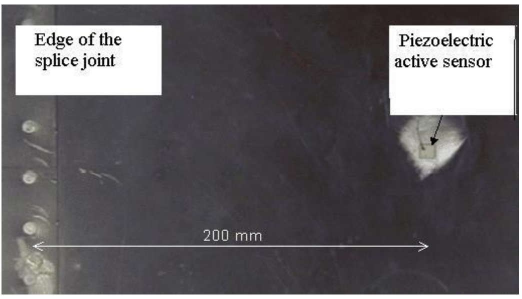


Figure 2b-Proof-of-concept EUSR experiment: Graphical user interface (EUSR-GUI) front panel

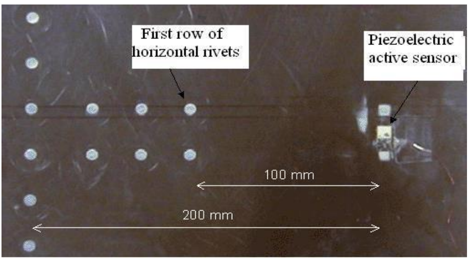
4, CRACK DETECTION USING PULSE ECHO METHOD

Wave propagation experiments were conducted on an aircraft panel to illustrate crack detection through the pulse-echo method. Figure 3 shows photographs of PWAS installation on three structural regions of the panel which are increasingly more complex. Adjacent to the photographs are the PWAS signals. The PWAS was placed in the same relative location, i.e., at 200 mm to the right of the vertical line of rivets. The first row of Figure 3 shows the situation with the lowest complexity, in which only the vertical line of rivets is present in the far left. The signal to the right of this photograph shows the initial bang (centered at around 5.3 micro-sec) and multiple reflections from the panel edges and the splice joint. The echoes start to arrive at approximately 60 µs. The second row of Figure 3 shows the vertical line of rivets in the far left and, in addition, a horizontal double row of rivets stretching towards the PWAS. The signal to the right shows that, in addition to the multiple echoes from the panel edges and the splice, the PWAS also receives backscatter echoes from the rivets located at the beginning of the horizontal row. These backscatter echoes are visible at around 42 µs. The third row in Figure 3 shows a region of the panel similar to that presented in the previous row, but having an addition feature: a simulated crack. emanating from the first rivet hole in the top horizontal row. The signal at the right of this photo shows features similar to those of the previous signal, but somehow stronger at the 42 µs position. The features at 42 µs correspond to the superposed reflections from the rivets and from the crack. The detection of the crack seems particularly difficult because the echoes from the crack and from the rivets are superposed. This difficulty was resolved by using the differential signal method, i.e., subtracting the signal presented in the second row from the signal presented in the third row.In practice, such a situation would correspond to subtracting a signal previously recorded on the undamaged structure from the signal recorded now on the damaged structure . Subtraction of these two signals yielded the signal presented in the last row of Figure 3.

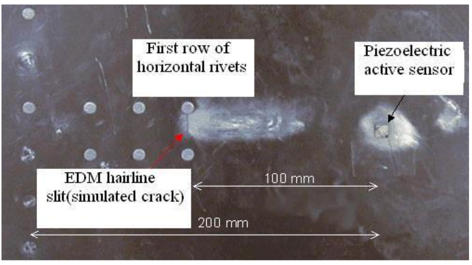
Thus, we concluded that PWAS are capable of clean and un-ambiguous detection of structural cracks.


Edge of the splice joint
Piezoelectric active sensor
200 mm

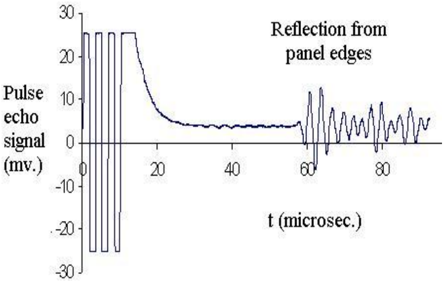
a.


First row of horizontal rivets
Piezoelectric active sensor
100 mm
200 mm

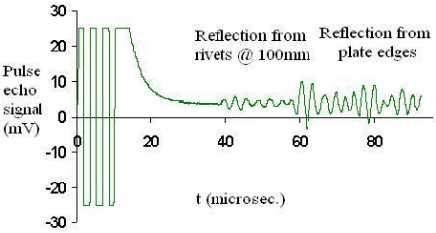
b.


First row of horizontal rivets
Piezoelectric active sensor
EDM hairline slit(simulated crack)
100 mm
200 mm

c.

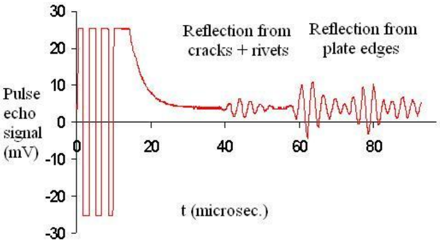

30
20
10
0
-10
-20
-30
Pulse echo signal (mv.)
0
20
40
60
80
t (microsec.)
Reflection from panel edges

d.


30
20
10
0
-10
-20
-30
Pulse echo signal (mV)
0
20
40
60
80
t (microsec.)
Reflection from rivets @ 100mm
Reflection from plate edges

e.

f.



g

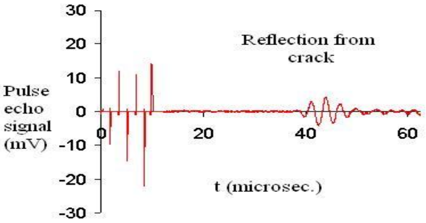


Figure 3-Crack-detection laboratory experiments on an aircraft panel:
3a-3c are specimens with increasing complexity; Figure 4b- E/M impedence spectrum showing radial changes 3d-3g represent the pulse-echo signals;
3g shows the crack detection through the differential signal method.

5, ELECTROMECHANICAL IMPEDENCE METHOD

PWAS transducers offer structural dynamics identification at hundreds of kHz and low MHz through the electromechanical (E/M) impedence method [8]. This approach is ideally suited for detecting minute damage because high frequencies imply small wavelength. PWAS-based electromechanical impedance spectroscopy (EMIS) is able to detect subtle changes in the high frequency structural dynamics at local scales. Such local changes in the high frequency structural dynamics are associated with the presence of incipient damage, which would not be detected by conventional modal analysis sensors that operate at lower frequencies.. Thus, EMIS method was found to have great potential for in-situ damage detection. The use of EMIS method for the detection of disbonds in adhesively assembled parts is illustrated in Figure 4. Three PWAS transducers (a1, a2, a3) were attached to an L-section stiffener bonded to a test panel. A disbond (DB1) was intentionally created during panel manufacturing. The PWAS a2 was mounted on top of the disbond, whereas PWAS a1 and a3 were mounted on regions of the stiffener were the bonding was in pristine condition (Figure 4a). The impedance spectrum from PWAS a1, a2, and a3 is presented in Figure 5b. It can be seen that the E/M impedance spectra for PWAS a1 and a3, which are located in areas with pristine bonding, are almost identical. However, the spectrum of PWAS a2, which is located on top of the disbond DB1, is entirely different, showing strong new resonant peaks and a clear increase in the response amplitude. These spectral changes are due to the changes in the local dynamics of the structure close to the disband.

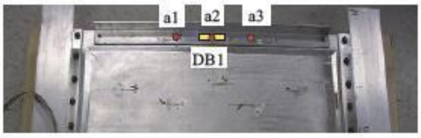


Figure 4a- PWAS a1,a2,a3 located on L-section stiffner bonded to test panel(a2 is above the disband DB1)

6, CONCLUSION AND FUTURE WORK

The military spends billions of dollars annually on inspection, identification, and repair of damage resulting from aircraft corrosion. Engines, transmissions, blades, cannisters and other system components include materials that degrade over time and are not often checked. The currently available methods for identifying aircraft corrosion damage involve expensive, labour intensive scheduled inspections, resulting in longer periods in depot, and reduction in aircraft availability. In order to increase aircraft safety, availability, and operational efficiency sensors are needed to provide inspection-free indicators of the existence of corrosion as well as the level of corrosive severity. A significant commercial benefit of NDE technology using PWAS lies in the cost and energy savings that can be gained through efficient condition-based maintenance of equipment, and especially in the harsh environments seen in the aerospace and industrial sectors. The paper concludes that the PWAS technology offer great opportunities for SHM applications. Presently Small Business Innovation Research (SBIR) Phase I project is investigating high-temperature wirelessly interrogated acoustic sensors for monitoring insulated structures such as piping and storage vessels that are in difficult to access locations and operate at elevated temperatures. Thus taking advantage of the advanced capabilities of the frequency-steered acoustic transducer (FSAT) work is in progress that will allow 2-D imaging with a simple interface that can be controlled by a low-power wireless system. If successful, this research will enable new in situ health monitoring capabilities at high-temperature. This emerging technology requires a sustained R&D effort to achieve its full developmental potential for applicability to full-scale aerospace vehicles.

ACKNOWLEDGMENT

The authors would like to thank Dr. Shyam Sunder Sharma (Assistant Prof. of physics department).

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