EMBEDDED NON-DESTRUCTIVE EVALUATION FOR DAMAGE DETECTION USING PIEZOELECTRIC WAFER ACTIVE SENSORS

Adrian Cuc  
University of South Carolina, USA  
Tel.: +01-803-777-0619, Fax: +01-803-777-0106, Email: aicuc000@engr.sc.edu

Victor Giurgiutiu  
University of South Carolina, USA  
Tel.: +01-803-777-7018, Fax: +01-803-777-0106, Email: victorg@sc.edu

ABSTRACT

Lamb wave methods have considerable potential for the inspection of metallic structures for two reasons: they do not require direct access to the bond region, and they are much more amenable to rapid scanning than are compression wave techniques. The paper will present a new approach to the nondestructive evaluation of metallic structures using small, unobtrusive piezoelectric active sensors permanently affixed on the surface of the structure.

KEYWORDS: Disbond, Lamb waves, NDE, PWAS, Ultrasonic.

1 INTRODUCTION

Structural health monitoring (SHM) is an emerging field with multiple applications. Many aerospace and civil infrastructure systems are at or beyond their design life; however, it is envisioned that they will remain in service for an extended period. SHM is one of the enabling technologies that will make this possible. Another potential SHM application is in new systems. By embedding SHM sensors and sensory systems into a new structure, the design paradigm can be changed and considerable savings in weight, size, and cost can be achieved. There are many ultrasonic nondestructive evaluation (NDE), non-destructive inspection (NDI), and non-destructive testing (NDT) techniques for identifying local damage and detect flaws in metallic structures. Ultrasonic NDE methods rely on elastic wave propagation and reflection within the material. They try to identify the wave field disturbances due to local damage and flaws. Ultrasonic testing involves one or more of the following measurements: time of flight (TOF; wave transit or delay), path length, frequency, phase angle, amplitude, impedance, and angle of wave deflection (reflection and refraction). Conventional ultrasonic methods include the pulse-echo, the pitch-catch (or pulse-transmission), and the pulse-resonance techniques.

This paper will investigate the possibility of using embedded ultrasonic non-destructive evaluation and the opportunity for developing embedded structural health monitoring. SHM determines the health of a structure by readings an array of sensors that are embedded (permanently attached) into the structure and monitored over time. SHM can be either passive or active. Passive SHM infers the state of the structure using passive sensors that are monitored over time and fed into a structural model. Active SHM uses active sensors that interrogate the structure to detect the presence of damage, and to estimate its extent and intensity. One active SHM method employs piezoelectric wafer active sensors (PWAS), which send and receive ultrasonic Lamb waves and determine the presence of cracks, delaminations, disbonds, and corrosion. Two approaches are being considered: (a) traveling waves; and (b) standing waves.

2 DETECTION STRATEGIES

Piezoelectric wafer active sensors (PWAS) are small, non-intrusive, and inexpensive piezoelectric wafers that are intimately affixed to the structure and can actively interrogating the structure. Piezoelectric active wafer sensors are non-resonant devices with wide band capabilities. They can be
wired into sensor arrays that are connected to data concentrators and wireless communicators. Piezoelectric wafer active sensors have captured the interest of academia and industry due to their low cost and non-intrusive nature.

2.1 Wave propagation methods with PWAS

Ultrasonic methods rely on elastic wave propagation and reflection within the material, and identify the field inhomogeneities due to local damage and flaws. Ultrasonic testing involves one or more of the following measurements: time of wave transit (or delay), path length, frequency, phase angle, amplitude, impedance, and angle of wave deflection (reflection and refraction).

2.1.1 Pitch-catch method

The pitch-catch method can be used to detect structural changes that take place between a transmitter transducer and a receiver transducer. The detection is performed through the examination of the guided wave amplitude, phase, dispersion, and time of flight in comparison with a “pristine” situation. Guided wave modes that are strongly influenced by small changes in the material stiffness and thickness (such as the A₀ Lamb wave) are well suited for this method. Typical applications include: (a) corrosion detection in metallic structures; (b) diffused damage in composites; (c) disbond detection in adhesive joints; (d) delamination detection in layered composites, etc. Pitch-catch method can also be used to detect the presence of cracks from the wave signal diffracted by the crack.

Figure 1 Embedded ultrasonics damage detection: pitch-catch method

The pitch-catch method detects damage from the changes that Lamb waves undergo when traveling through a damaged region. The method uses the transducers in pairs, one as transmitter, the other as receiver. In the embedded pitch-catch method (Figure 1), the transducers are either permanently attached to the structure or inserted between the layers of composite layup.

2.1.2 Pulse-echo method

In conventional NDE, the pulse echo method has traditionally been used for through-the-thickness testing. For large area inspection, through-the-thickness testing requires manual or mechanical moving of the transducer over the area of interest, which is labor intensive and time consuming. It seems apparent that guided-wave pulse echo seems more appropriate, since wide coverage could be achieved from a single location. For crack-detection with the pulse-echo method, an appropriate Lamb-wave mode must be selected. Giurgiutiu et al (2003) used finite element simulation to show that the S₀ Lamb waves can give much better reflections from through-the-thickness cracks than the A₀ Lamb waves. This effect can be attributed to S₀ being: (a) better reflected from the crack; and (b) much less dispersive. The first fact gives a strong signal, while the second ensures that the wave packet is compact and easy to interpret.

Figure 2 Embedded ultrasonics damage detection: pulse-echo method

The use of Lamb-wave pulse echo methods with embedded PWAS follows the general principles of conventional Lamb-wave NDE. A PWAS transducer attached to the structure acts as both transmitter and detector of acoustic guided waves traveling in the structure. The wave sent by the PWAS is partially reflected at the crack. The echo is captured at the same PWAS acting as receiver (Figure 2). For the method to be successful, it is important that a low-dispersion Lamb wave is used. The selection of such a wave, e.g., the S₀ mode, is achieved through the Lamb-wave tuning methods.

2.2 Standing wave methods with PWAS

The impedance method is a damage detection technique complementary to the wave propagation techniques. The mechanical impedance method consists of exciting vibrations of bonded plates using a specialized transducer that simultaneously measures the applied normal force and the induced velocity. The electro-mechanical (E/M) impedance method is an emerging technology that offers distinctive advantage over the mechanical impedance method. While the mechanical impedance method uses normal force excitation, the E/M impedance method uses in-plane strain. The mechanical impedance transducer measures mechanical quantities (force and velocity/acceleration) to indirectly calculate the mechanical impedance, while the E/M impedance active sensor measures the E/M impedance directly.
as an electrical quantity. The principles of the E/M impedance technique are illustrated in Figure 3:

\[
v(t) = V \sin(\omega t) \quad \text{PWAS transducer}
\]

\[
i(t) = I \sin(\omega t + \phi)
\]

Figure 3 Embedded ultrasonics damage detection: electro-mechanical impedance method

The effect of a piezoelectric wafer active sensor affixed to the structure is to apply a local strain parallel to the surface that creates stationary elastic waves in the structure. Through the mechanical coupling between the PWAS and the host structure, on one hand, and through the electro-mechanical transduction inside the PWAS, on the other hand, the drive-point structural impedance is directly reflected into the effective electrical impedance as seen at the active sensor terminals. The apparent electro-mechanical impedance of the piezoelectric active sensor as coupled to the host structure is:

\[
Z(\omega) = \left[ i\omega C \left( 1 - \kappa_{31}^2 \frac{Z_{str}(\omega)}{Z_{PWAS}(\omega) + Z_{str}(\omega)} \right) \right]^{-1}
\]

where \( Z(\omega) \) is the equivalent electromechanical admittance as seen at the PWAS terminals, \( C \) is the zero-load capacitance of the PWAS, \( \kappa_{31} \) is the electromechanical cross coupling coefficient of the PWAS \( (\kappa_{31} = d_{13} / \sqrt{\varepsilon_{11} e_{33}}) \), \( Z_{str} \) is the impedance of the structure, and \( Z_{PWAS} \) is the impedance of the PWAS.

3 EXPERIMENTAL RESULTS

The paper will address three cases: first an aluminum lap-joint specimen was fabricated, instrumented and tested second, a helicopter blade was instrumented and tested and third spacecraft panels were instrumented and analyzed for different types of flaws. In the first two cases the purpose was to successfully send and receive guided waves (Lamb waves) through adhesively bonded materials.

3.1 Lap-joint specimen

An aluminum lap-joint specimen was fabricated using two aluminum 2024T3 stripes as shown in Figure 4. The overlap of the two aluminum stripes is 20mm. The disbonds were artificially created using Mylar® polyester film that was introduced between the two aluminum stripes and produced a discontinuity of the adhesive layer. Next, the specimen was instrumented with an array of PWAS sensors as presented in Figure 4.

To prove successful transmission and reception of Lamb waves, the pitch-catch method was used. The instrumentation set-up is shown in Figure 5. An HP 33210 signal generator was used to produce a 3-count sinusoidal tone burst with a frequency of 390 kHz.

Figure 4 Location of the PWAS on the lap-joint specimen

Figure 5 Schematic of the instrumentation set-up

The results shown in Figure 6 clearly demonstrate the capability of our PWAS to send and receive Lamb waves in the aluminum material itself and along the bond line. Figure 7 presents the attenuation of the Lamb waves traveling in the aluminum layer only and along the bond line.
Figure 6 Traveling S\textsubscript{0} mode Lamb waves: (a) single layer; (b) along the bond line

The energy of the signal traveling along the bond line is less than the energy of the signal traveling outside the bond line, thus the signal is weaker, the adhesive layer absorbing part of the energy of the transmitted wave.

\begin{align*}
y &= 0.3413e^{-0.0066x} \\
R^2 &= 0.9841 \\
y &= 0.1643e^{-0.0056x} \\
R^2 &= 0.9806
\end{align*}

Figure 7 Attenuation of the S\textsubscript{0} Lamb wave mode

3.2 Helicopter blade

A helicopter main rotor blade was instrumented with an array of PWAS sensors as shown in Figure 8. The array consists of 15 sensors disposed in five columns and three rows. The sensors on the first and the third row are mounted along the bond line (Figure 8) while the sensors on the second row are mounted on the skin of the blade.

The instrumentation setup consists of an HP 33120 signal generator to generate the excitation signal, a Tektronix TDS210 digital oscilloscope to collect the signal from the PWAS, and a computer to store and analyze the signal.

Figure 8 (a) Location of the PWAS on the helicopter blade; (b) schematic of the instrumentation setup

The capability of successfully sending Lamb waves from one sensor and receiving the signal on the other sensors was investigated. A schematic of the instrumentation setup is presented in Figure 8 along with the location of the PWAS sensors on the main rotor blade. Using the signal generator, a 3-count sinusoidal burst signal at a frequency of 330 kHz was sent from sensor A\textsubscript{1} and received at sensors B\textsubscript{1} and C\textsubscript{1} along the bond line, as shown in Figure 9a. Also the same signal was sent from sensor A\textsubscript{1} to sensor B\textsubscript{1}, B\textsubscript{2} and B\textsubscript{3} across the bond line as shown in Figure 9b. The results clearly show the possibility of sending and receiving surface Lamb waves along and across the bond line of a helicopter blade.
3.3 Spacecraft panel specimens

Two aluminum test panels were fabricated by NextGen Aeronautics, Inc (Figure 11).

The stiffeners were bonded to the aluminum skin using a structural adhesive, Hysol EA 9394. Damages were artificially introduced in the two specimens including cracks (CK), corrosions (CR), disbonds (DB), and cracks under bolts (CB). The instrumentation set-up for Panel 1 is presented in Figure 12.

Panel 1 contains disbonds, cracks and corrosions. The disbonds are located between the stiffeners and the skin. They are of two types: partial disbonds DB1 and DB3, and through disbonds DB2 and DB4. The corrosions are simulated as machined areas. The four cracks presented are in the shape of a slit and are through cracks located on the skin of the panel.

The results for the pulse-echo method used for damage detection of the disbonds located on the Panel 1 are presented in Figure 13.
seen in Figure 14 that the resonant spectrums of the signals from PWAS a1 and a3 located on an area with good bond are almost identical. The resonant spectrum from PWAS a2 located on the disbond DB1 is very different showing new strong resonant peaks associated with the presence of the disbond.

4 CONCLUSIONS

The paper presented the general concept of embedded nondestructive evaluation for damage detection using piezoelectric wafer active sensors. Next we addressed the problem of sending and receiving Lamb waves in adhesively-bonded structures using embedded piezoelectric wafer active sensors (PWAS). Two cases have been considered: first, an aluminum lap-joint that was fabricated, instrumented and tested, and second a helicopter blade with bonded titanium C-sections that was instrumented and tested. Last, the results using wave propagation methods (pitch-catch and pulse-echo) and standing wave methods (electromechanical impedance) on realistic specimens were presented.

ACKNOWLEDGMENTS

The financial support of NASA STTR program through Phase I topic T7-02 is gratefully acknowledged.

REFERENCES