INTER-DIGITIZED TRANSDUCERS (IDTS) FOR INTEGRATED STRUCTURAL HEALTH MONITORING (ISHM) APPLICATIONS

J. K. Na

NDE Group, EWI
1250 Arthur E. Adams Drive
Columbus, OH 43221 USA
j.na@ewi.org

ABSTRACT

Single element piezoelectric plates having inter-digitized electrode patterns, specifically tuned to operate at several hundred kHz to several MHz of frequencies, have been designed and fabricated by a laser micro machining process. These narrow band thin plate sensors are extremely effective to induce Rayleigh surface waves directly on the surfaces of various materials such as metals, plastics and composites. Ultrasonic signatures of flaws, defects and damages on the surfaces of materials are easy to interpret with IDT sensors due to the non-dispersive wave property of Rayleigh waves. Laboratory tests proved that detection of a deterministic fatigue crack on a structurally critical component of aircraft is straightforward in terms of changes in amplitudes. As a first step toward ISHM application of IDT sensors to composite materials, the ultrasonic properties of the test panels made from polyester and glass fiber have been measured with respect to the fiber directions. Unlike isotropic metallic structures, anisotropy caused by glass fiber directions affects the ultrasonic properties as well as detection of defects and flaws in composite panels. Artificially induced surface cracks, delamination and impact damage on test panels are used to quantify the size, location and severity of damage in terms of changes in amplitudes. It is estimated to cover a distance close to one meter with a set of IDT sensors, one transmitter and two receivers, for the composite panels, while the distance coverage can reach several meters for metallic structures at a several hundred kHz of frequency. The primary motives behind ISHM are as follows: 1) monitor damage and deterioration as the structure ages; 2) provide early warning of imminent failure; 3) provide data to plan extension of life through condition based maintenance; and 4) significantly reduce the on-going cost of inspection and maintenance programs.

Keywords: Inter-digital Transducer (IDT), Integrated Structural Health Monitoring (ISHM), Rayleigh Surface Waves

2011 CANSMART CINDE IZFP
INTRODUCTION

There are many different ways to generate Rayleigh surface waves into various types of materials [1]. Among them, most commonly used methods are using a wedge or a comb as shown in Figure 1. In both cases, Rayleigh waves are generated by converting a compressional wave that is generated by a longitudinal mode piezoelectric plate, which lowers energy efficiency to induce surface waves into materials especially for a structural health monitoring application. The use of wedge or comb is not practical for ISHM applications.

Years of effort were devoted to optimize designs of narrow-band single element inter-digitized transducers for ISHM applications through laboratory testing and evaluation. The designs of IDT electrode patterns were originally developed for the telecommunication industry as a high fidelity/high frequency SAW filter applications [2-4]. Unlike the photo-lithography process used for fabricating SAW filters, the fabrication process used for the current IDT sensors was a laser micro-machining technique which utilizes an extremely high pulse rate laser beam, in the order of $10^{-15}$ per second, to form a precise inter-digitized electrode pattern on a piezoelectric plate as shown in Figure 2. It is important to have a tight tolerance, less than a few microns for megahertz range sensors, for the finger width and the spacing between fingers for maximize surface wave output.

![Fig. 1](image1.png)  
**Fig. 1:** Conventional Rayleigh wave generation methods using a wedge and a comb.

![Fig. 2](image2.png)  
**Fig. 2:** Digital photos showing (a) overall electrode pattern of an actual IDT and (b) close-up view of an electrode finger and finger spacing.
EXPERIMENT

IDT sensors

Number of IDT sensors were designed, fabricated and tested. The photo in Figure 3(a) shows some of the IDT sensors used for the current ISHM investigations. The ultrasonic surface wave field generated by an IDT is seen to be largely bi-directional in nature as shown in Figure 3(b). The main beam spread was measured to be less than ±5 degrees for a miniature five finger pair sensor used for this visualization. Additional detailed information about the characteristics of IDT sensors can be found in a previous publication [5].

![IDT sensors](image1)

(a) Various size IDT sensors  (b) Bi-directional Rayleigh surface waves

**Fig. 3**: IDT sensors (a) fabricated by a laser micro-machining technique and (b) bi-directional Rayleigh surface waves generated by an IDT.

Interaction of surface waves with a surface breaking crack

A visualized image of an ultrasonic surface wave interacting with a fatigue crack is shown in Figure 4. From the image, it is clear that some of the incident beam is reflected by the top portion of the crack near the start notch, while the other part of the beam transmits through the crack where the interfaces are tightly in contact. Even though the fatigue crack on the aluminum block was a through crack, the image in Figure 4 suggests that there are regions contacting each other inside the crack so that the elastic energy can pass through.

![Interaction of surface wave](image2)

**Fig. 4**: Interaction of surface wave with a tightly closed fatigue crack.
Compact tension fatigue test specimens

The performance of the IDT sensors was assessed using three compact tension (CT) fatigue test specimens before the flight simulated fatigue testing on a real aircraft structure. The CT specimens were designed according to ASTM standard E300-05-A4 and fabricated from aircraft grade aluminum 7075 alloy with overall dimensions of 76 mm x 76 mm and 12.7 mm in thickness. The photo in Figure 5(a) shows one of the CT test specimens with a pair of IDT sensors temporarily bonded to its surface. Figure 5(b) shows the fatigue test setup with a CT specimen mounted on an MTS fatigue loading frame. A digital micrometer attached on the frame was used to measure the length of a fatigue crack as it grew.

![CT specimen with IDT sensors](image1)
![Fatigue test setup](image2)

(a) CT specimen with IDT sensors  (b) Fatigue test setup

Fig. 5: Digital photos of a CT specimen and the fatigue test setup.

Aircraft structural component

IDT sensors similar to the ones evaluated using the CT specimens were used to perform fatigue testing on an actual aircraft part. Figure 6 shows the part of the aircraft structure used for the test. The overall dimensions of the fatigue specimen are approximately 2 m x 0.5 m. The schematic drawing in Figure 7 shows one of the cut-out window sections on the part and the locations of IDT sensors. Since IDT sensors generate surface wave signals bi-directionally, the entire surface of the cut-out window can be monitored with two sensors. The signal paths are defined as the upper and lower paths with respect to the locations of the sensors on the side wall (see Figure 7).

![Fatigue test setup](image3)

Fig. 6: Representative aircraft component subjected to fatigue testing.
**Fig. 7**: Schematic drawing of IDT sensors bonded on the side wall of cut-out window section in a pitch-catch mode configuration.

**IDT sensors for windmill blade composite panel**

A schematic drawing of an IDT sensor specifically designed for composite materials and the measurement result for the beam pattern are shown in Figure 8. For the beam pattern measurements shown in Figure 8(b), a transmitting IDT sensor was fixed at a position and the receiving IDT sensor was adjusted for its angular position at a distance 10 cm away from the transmitter. Data was collected every 3°. There is a slight asymmetry in the beam patterns; the left side shows a narrower width with lower peak output amplitude at 180° than the right side. The reason for this asymmetry in beam patterns is thought to be the extra material in the electrode tap area located on the left side. A half inch thick glass plate was used for this measurement.

**Fig. 8**: (a) A typical schematic drawing for a 10-finger-pair IDT sensor and (b) its bi-directional surface wave beam pattern.
Photos of the composite test panels are shown in Figure 9. Due to the anisotropy elastic properties of the composite test panels, it was necessary to define new material coordinates as shown in Figure 10. In each ply, there are two 45° layers on top of each other with orthogonally aligned fiber directions and a randomly chopped layer on the bottom. This configuration repeats for the other three plies as well. The thickness of composite skin on the 4-ply test panel is approximately 5 mm as indicated in Figure 9(c).

**Fig. 9:** Photos of (a) flat composite panels, (b) side view of a 4-ply panel and (c) its schematic drawing for the cross-sectional view.

**Fig. 10:** Definition of material coordinates used for ultrasonic measurements on BXM-1708 fiberglass composite panels.

**EXPERIMENTAL RESULTS AND DISCUSSIONS**

**CT fatigue test**

As fatigue cracks initiated and grew across the ultrasonic field on a compact tension specimen, both the length of crack and the signals of IDT sensors were monitored and measured in the

2011 CANSMART CINDE IZFP
pitch-catch mode. The same fatigue test was repeated three times on three CT specimens. The results of all three CT fatigue testing are shown in Figure 11. In this graph, the amplitudes are normalized to the initial amplitude levels and the results shown in the graph are repeatable.

![Normalized Amplitude vs Crack Length](image1)

**Fig. 11:** Experimental results of three CT fatigue tests in the pitch-catch mode.

**Aircraft component fatigue test**

Results from the aircraft component fatigue test are presented in Figure 12. During the course of the fatigue test, one of three monitoring locations showed evidence of crack initiation and growth at 1.5 million cycles, while the other two locations showed no indication of damage at all. The results of one of the two non-cracked locations are provided in Figure 12(a), where the plot shows no changes in signal amplitude as a function of fatigue cycle. In Figure 12(b), there is an amplitude decrease in the lower path after 1.5 million cycles indicating a crack was induced on the surface.

![Normalized Amplitude vs Fatigue](image2)

(a) No indication of crack

(b) Indication of crack

**Fig. 12:** Results of fatigue test on a critical aircraft component.
Windmill blade composite panels

Crack: The illustrations in Figure 13 show how the simulation was made for a growing crack interacting with the surface wave field at three different angles. The angle between the wave propagation direction and the crack were initially set to be 90° and subsequently changed to be 66° and 114° to the propagation direction to simulate a crack growing into the sound field at an angle different from 90°. This was done by moving both transmitting and receiving sensors with respect to the cut while maintaining the sensor distance at 30 cm apart and keeping the crack in the middle.

![Fig. 13: Simulation of a crack interacting with the sound field at different angles.](image)

From the experimental results shown in Figure 14, one can notice that the amplitude drops to a minimum value close to -20 dB as the crack location reaches to the middle of the sound field and then increases back to the initial level for all three cases. In the case of 90° interaction, the amplitude decrease and increase are continuous with no noticeable abnormal behavior. In the cases of both 66° and 114°, however, an additional peak shows up at the distance about -15 mm and +15 mm, respectively. These peaks may be due to the crack tip scattering as the crack propagates into the sound field.

![Fig. 14: Experimental results showing changes in amplitude as a simulated crack grows into the surface wave field at different incident angles.](image)

2011 CANSMART CINDE IZFP
Impact: A carpenter’s hammer weighing approximately 500 grams was used to induce impact damage on a 4-ply composite panel. The distance from the top of the test panel to the bottom of the hammer head was kept at a distance of 20 cm for each drop. For repeatable impact damage on the same spot, the end of the hammer handle was rested on the same spot and the hammer was released for a free drop. The angle between the hammer’s handle and the top of the composite panel was chosen to be 45° for each drop.

Ultrasonic measurements were made at different radial angles with an interval of 45° while maintaining the total distance between the transmitter and receiver at 20 cm as shown in Figure 15(a). The experimental results are depicted in Figure 15(b). The amplitude level measured before the impact damage was used as a reference signal level for decibel calculations. As noticed from the polar graph, the overall amplitude decreases as the impact damage increases. The very symmetrical diamond-like amplitude pattern changes into more irregular shape after 15 and 20 blows with decreasing amplitudes along all angles. After an additional 200 blows, the amplitude drop was approximately 10 dB in average. Based on the current experimental results, the effect of fiber direction dependency in the undamaged condition of the panel appears to disappear at an early stage of impact damage. This may be the indication of glass fiber breakages and eventually the development of micro-cracks in the matrix material as the level of impact damage increases.

![Diagram of ultrasonic measurement setup](image)

**Fig. 15:** (a) A schematic drawing showing ultrasonic measurement set up for impact damage on the 4-ply composite test panel. (b) Decrease in the amplitude measured in dB in the impact damaged region of the composite panel with 500 kHz IDT sensors.

**SUMMARY**

Surface wave generating narrow band single element IDT sensors have been designed, fabricated and tested for integrated structural health monitoring applications. Surface breaking fatigue cracks were detected with custom designed IDT sensors on CT fatigue specimens under laboratory conditions. Surface wave signals monitored with the pitch-catch method showed an approximately 80% decrease in amplitude from initial values as the crack lengths reached about 5 mm. In terms of repeatability, the pitch-catch signal showed less than 5% variation in the final amplitude among three CT test specimens. It was also demonstrated that the IDT sensors strategically placed in critical locations on a representative aircraft structural component can
detect surface breaking fatigue cracks occurring in anticipated locations. Surface wave signals detected with the IDT sensors successfully demonstrated changes in the reflected/transmitted amplitudes due to the presence of a fatigue crack. The amplitude of the signal detected by the pitch-catch sensors on the inner wall of the cut-out section decreased to 50% of the initial value as the fatigue cycle past 1.5 million which was estimated to be about 80% of the fatigue life for the structure.

IDT sensors operating at 500 kHz showed promising results in terms of crack and impact detection. Based on the present work, decrease in amplitude can be correlated to the crack length as the sound field is cut off by a growing crack at various angles relative the ultrasonic wave propagation direction. Accumulated impact damage can also be detected in terms of anisotropy properties of composite materials as well as the fiber breakage. As the impact damage was accumulated, the symmetrical diamond-like shaped amplitude response pattern collapsed into an irregular shape indicating that the glass fibers got damaged initially and micro-cracks in the matrix material caused amplitude drops eventually.

REFERENCES