WIRELESS NONDESTRUCTIVE INSPECTION OF AIRCRAFT WING WITH ULTRASONIC GUIDED WAVES

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Abstract: A prototype wireless guided wave inspection system is developed to inspect layered structures such as aircraft wing. The system includes a stationary antenna and an active antenna as transceivers, an on-board antenna as transponder, and PVDF comb transducers for generating and receiving ultrasonic Lamb waves. Preliminary experiments on a 0.8mm aluminium plate with a 12mm long, 50% through-wall-depth crack clearly demonstrated its feasibility of defect detection. Potential applications on an E2 plane wing section are also presented. This system showed great potential of remote, leave-in-place and in-service defect detection and condition monitoring.

Introduction: The flight environment of an aircraft is usually very harsh due to large changes in humidity, temperature, pressure, speed, and loading conditions. These effects cause a lot of stress to aircraft frame. As a result, corrosion, delamination, cracks, disbonds, and other failures creep in once the aircraft is in service for some time. Fault diagnosis and prognosis is very important in health monitoring or condition based maintenance of the aircraft structures. If one can measure the degradation of a component before it actually fails, it will provide ample time for maintenance engineers to schedule a repair, and to purchase or fabricate replacement components before the components actually fail. The end result will be lower cost and higher availability.

Ultrasonic guided waves have been used in non-destructive inspection (NDI) of various defects in aircraft structures[1-3], with major advantages like fast scanning capabilities, low cost, and long range inspection. Small and reliable guided wave sensors can also be leave-in-place on the structures for online monitoring[4,5], which is more convenient for real time damage evaluation. All current data acquisition techniques, however, still rely on cable connections from a waveform generator to the inspection sensors, and then to a waveform displayer or oscilloscope for analysis.

In this paper, we proposed a novel wireless system for structural integrity monitoring of an aircraft. The prototype system includes a passive antenna as a transmitter, an on-board antenna as transponder, a PVDF comb transducer for generating and receiving ultrasonic Lamb waves in a layered structure, and a portable active antenna as a receiver. A series of experiments on a 0.8mm thick aluminium plate with a 12mm long, 50% through-the-wall crack clearly showed its feasibility in defect detection. Conventional wired approach and semi-wireless approach are also presented for comparison. Some practical leave-on-board antennae for aircraft wings are also discussed, along with preliminary experiments.

Approaches: One of the objectives of this study is that NDI sensors should be low-cost, compact, passive, conformable to the aircraft structure, and can be interrogated in a wireless manner. The wireless capability allows the aircraft to be monitored all the time. Boeing has performed an internal study, which concludes that 85% of maintenance effort is spent on tearing down and re-assembling the components. Only 15% of labour is spent on actual inspection. Hence the maintenance cost can be saved significantly by a wireless leave-in-place approach. For this objective to be materialized, we proposed a technical approach as shown in Figure 1. That is, a PVDF guided wave sensor is attached to the test structure, with its input/output connected to an on-board antenna to feed in interrogate electrical signal and send out its response. The interrogate signal can be transmitted by a transmission antenna through a cable connected to the signal generator, and the return signal captured by a receiving antenna cable connected to a signal receiver. In this case, both the transmission and receiving antennae can be moved around and collect information about the health status of the structure. The conventional wired approach does not use antennae as information transponder; usually co-axial cables are utilized to connect the signal generator, the sensor and the signal receiver together and it is the state-of-practice in industry. The choice of PVDF sensor is obvious since it is low-cost, compact, passive, conformable to the test structure, and easy installation[6]. We will discuss more about its design and utilization in the next subsection.

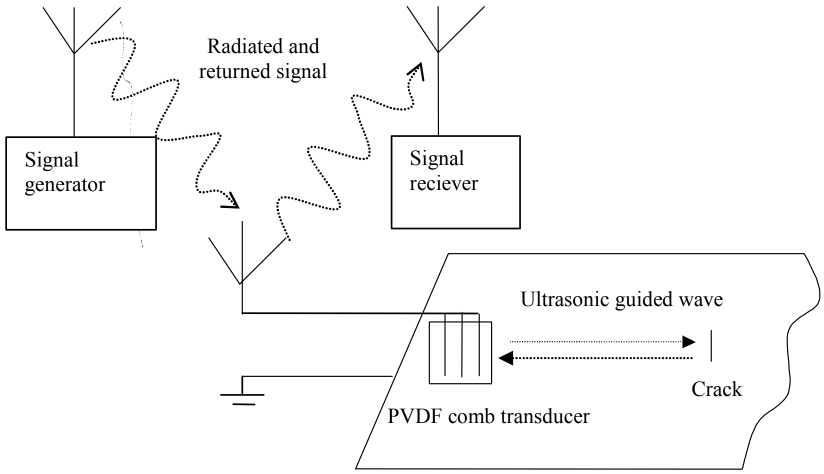


FIGURE 1 - The schematic view of wireless inspection system for crack detection.

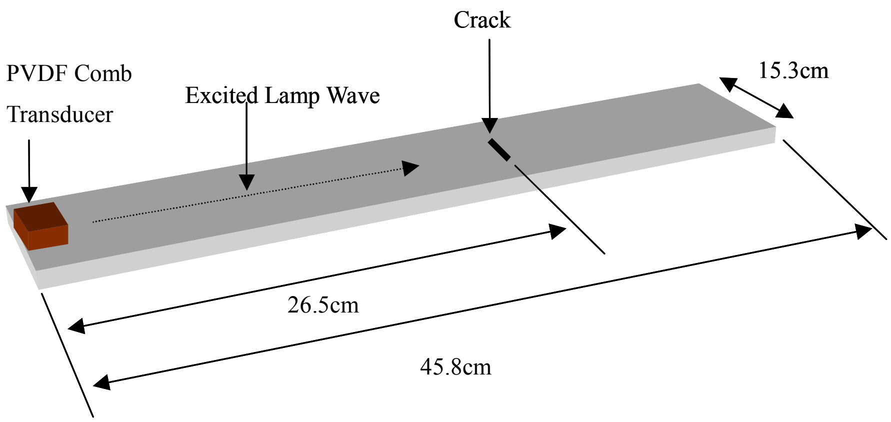


FIGURE 2 - Test specimen with a PVDF comb transducer bonded on the aluminium plate.

An aluminium plate specimen with a simulated notch defect shown in Figure 2 was used in this study. Some dimensions are shown in the figure. The plate thickness is 0.8 mm; the notch is about 12mm long, 2mm wide and 0.4mm in depth. Guided Lamb waves are generated by a PVDF comb transducer which is of area 45mm by 10mm, thickness less than 1mm, and mounted on the plate. The transducer can either be set in a pulse-echo mode or two transducers can lie side by side in a through-transmission mode to simulate pulse-echo so that the defect signal reflected from the crack can be captured.

Based on wave structural characteristics[7], there are several guidelines for guided wave sensor design with respect to mode and frequency selection. First, the working frequency should be low to reduce the complexity of mode separation and mode conversion at the defect. Second, the mode and frequency should not be so low that the guided wave may miss small defects and its resolution deteriorates too much. Third, the sensor should be tuned in mode and frequency such that the wave mode displacement and stress fields are concentrated at the defect level in the plate. For example in this paper, we would like to inspect a surface-breaking crack on an aluminium plate. Thus most guided wave energy should concentrate on the surface of the plate for better sensitivity. Fourth, the wave mode should be as less dispersive as possible since dispersion often leads to wave packet shape change and spreading, which usually complicates the signal interpretation.

Among either anti-symmetric (*A*) or symmetric (*S*) modes at the lower frequency range, e.g., *fd* value below 3, where *f* is the working frequency and *d* is the thickness of the plate, a mode associated with high energy at the surface of the plate is the A_1 mode. After calculating the dispersion curve and wave structure, the A_1 mode with the *fd* value at 2.5 MHz-mm is selected because there is minimum wave dispersion or minimum wave packet spreading. The wave structural characteristic of the A_1 mode Lamb wave is shown in Figure 3, in which the in-plane and out-plane displacements components are plotted against the plate thickness. The point of maximum group velocity for A_1 on group velocity dispersion curve is marked in Figure 4. The value of *fd* of the maximum group velocity point is 2.5MHz. Since the thickness of plate to be tested is 0.8mm, the operating frequency of Lamb wave sensor is found to be around 3.2 MHz. Figure 5 marks the operation point on the phase velocity dispersion curve which will be used for the actual sensor design.

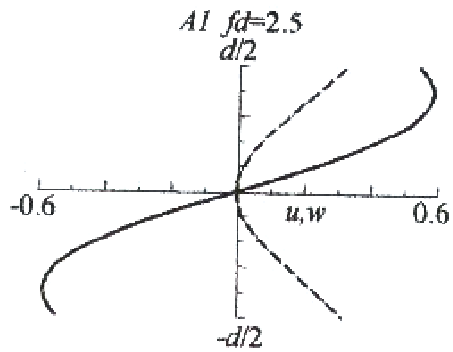
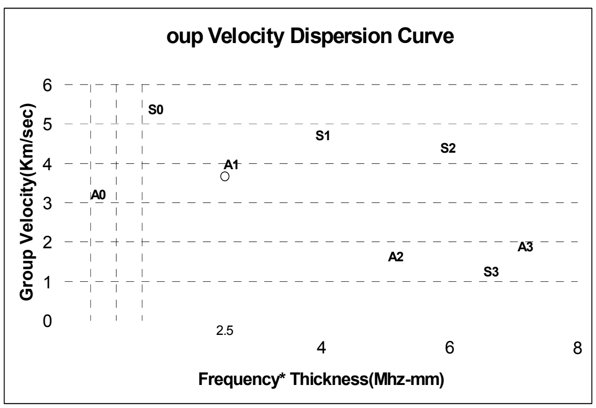


FIGURE 3 - Wave structure for A_1 mode of an aluminum plate for $fd = 2.5$. Solid curve denotes the in-plane displacement and dashed curve is the out-plane displacement



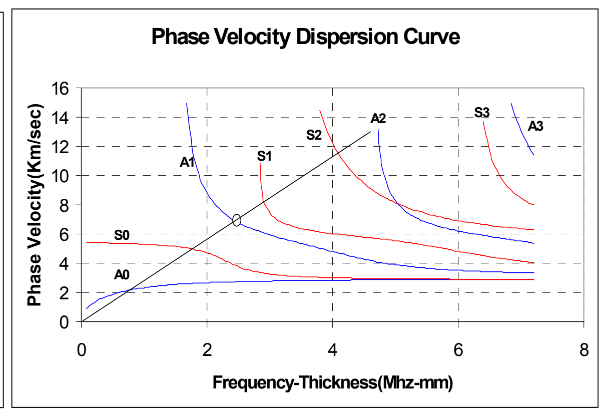
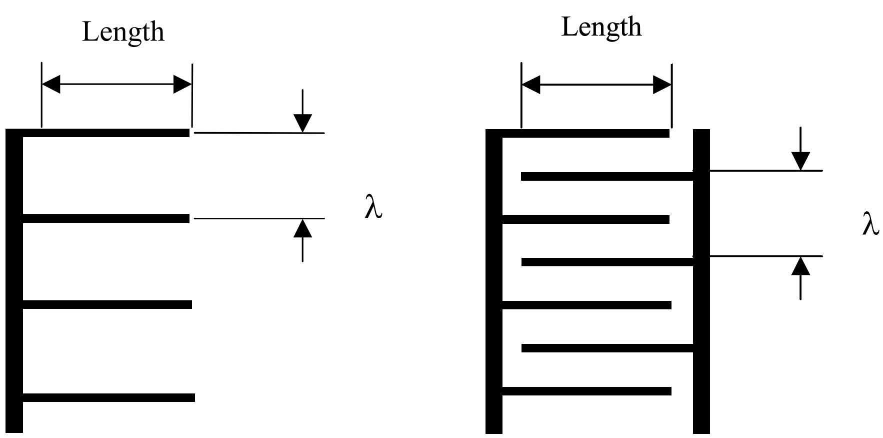


FIGURE 4 - The Group velocity dispersion curve plate (0.8mm).

FIGURE 5 - The Phase velocity dispersion for an aluminum curve for an aluminum plate (0.8mm).



(a)

(b)

FIGURE 6 - Electrode pattern of PVDF guided wave sensors. (a) The comb pattern. (b) Inter-digital pattern.

A PVDF comb sensor is designed as shown in Figure 6(a), in which the comb pattern of the electrodes on one side of a PVDF film is illustrated. The distance between two combs is determined by $\lambda = c_p / f$ where c_p is phase velocity and f is frequency. All the combs are connected and fed by a tone-burst signal; a common ground electrode covering the whole area of the pattern is on the other side of the PVDF film. This sensor can generate and receive ultrasonic guided waves in a pulse echo mode. For two sensors working in a transmission mode to simulate pulse-echo, an inter-digital pattern was implemented (Fig. 6b), with one group of combs sending out wave energy and the other group receiving the returns.

Our preliminary inspection system is built upon a PC system. It consists of a Matec® TB-1000 tone-burst signal generation and receiving card, Datel® PCI-417M2 high speed data acquisition board (DAQ), and a commercial off-the-shelf Vectronics® active antenna and hand-made passive monopole antennae. The TB-1000 card can generate windowed sinusoidal wave of frequency from 50 kHz to 20 MHz and voltage peak-to-peak value 300 volt, and has up to 70 dB signal gain in the receiver side. It can work both in the pulse echo mode and the through transmission mode. The PCA-417M2 DAQ has two channels, with maximum sampling rate at 40 MHz. The Vectronics active antenna provides amplified reception of broadcast, short wave or amateur radio signals from 300 kHz to 40 MHz. The passive antennae are made of aluminum tubes of 580mm long and 6.5mm in diameter. The feeding point is at the end of the tube. Note that this design is not optimized yet for 3 MHz electromagnetic waves generation and reception; it is only used for demonstration of concept.

Results:

Wired Inspection Case

The purpose of measuring the notch through wired approach is to test the functionality of the thin PVDF comb transducer. Moreover, this experiment will provide the best baseline performance for crack detection. The transducer is working in the pulse-echo mode for the wired inspection approach. For the experiment, a tone-burst signal of center frequency 3.215 MHz and time duration 6 microseconds was input into the PVDF transducer through a co-axial cable. Guided waves generated by the PVDF transducer propagated along the plate. When hitting the notch and the end-edge, part of the wave energy returned back and was picked up by the PVDF sensor, converted back into electrical signal, and collected by the data acquisition card. The waveform is digitized and shown on the computer screen. Figure 7 shows the received signal.

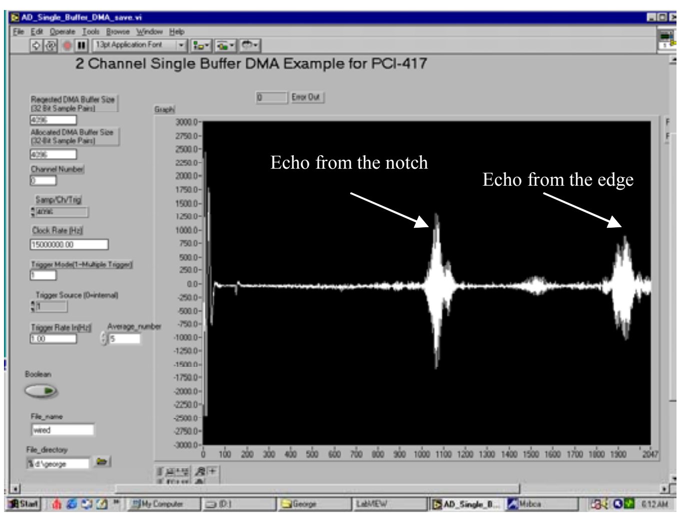


FIGURE 7 - Wired inspection waveform of the 12mm long 50% through wall notch in a 0.8mm thick aluminum plate 26.5mm away from the sensor

The notch signal is clearly seen and the signal to noise ratio is excellent. Note that the A_0 mode Lamb wave echo from the notch (the small peak between the two large peaks) is also shown, but with much less amplitude. With this wired approach worked well, the semi-wireless and total wireless inspection experiments were continued and shown in the next section.

Semi-Wireless Inspection

The semi-wireless approach was accomplished by substituting the receiving side cable with an on-board monopole antenna and active receiving antenna. The on-board antenna helped efficient transmission of electronic signal concerted at the PVDF sensor to the receiver antenna. The setup is shown in Figure 8. The tone-burst signal generated by the TB-1000 card was still the input to the PVDF transducer through a co-axial cable; on the receiver side, a passive monopole antenna was used as an on-board antenna for transmitting back the PVDF sensor signals. The on-board antenna is wire-connected to the PVDF sensor. The active antenna received the signal and sent it to the data acquisition card for waveform display. The waveform after 25 times of averaging is shown in Figure 9.

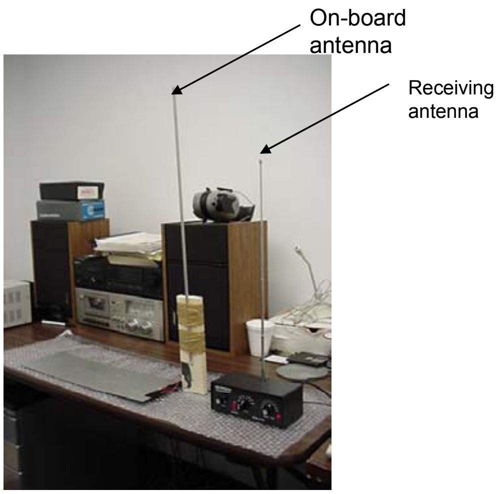


FIGURE 8 - Semi-wireless inspection system setup.

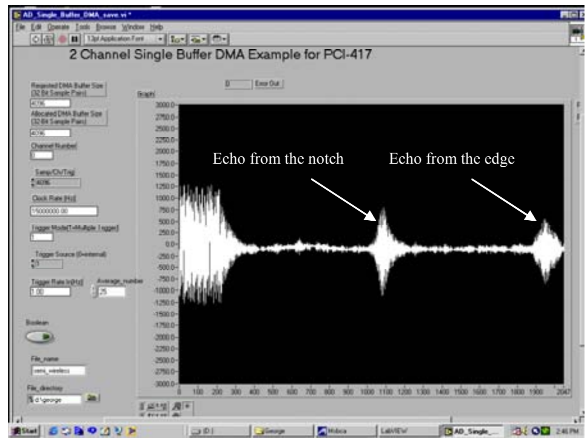


FIGURE 9 - Semi-wireless inspection results of the of the 12mm long 50% through wall notch in a 0.8mm thick aluminium plate 26.5mm away from the sensor

Compared with the results of using the wired approach, we can see that the using antennae for signal transmission certainly decreased the signal efficiency. However, it is a trade-off to be able to collect the data wirelessly. Nevertheless, the signal obtained is not bad at all.

Wireless Inspection

Our preliminary setup made use of a separate signal transmission antenna since the Vectronics® active antenna does not have signal transmission function. As shown in Figure 10, the tone-burst card output was connected to a monopole antenna through a coaxial cable. The signal was then emitted out. On the structure to be tested, an on-board monopole antenna was wired to the PVDF transducer. Thus the signal emitted from the transmission antenna was picked up by the on-board antenna and the energy was converted to ultrasonic guided waves through the PVDF transducer. The guided waves propagated along the plate, once it hit a crack, part of the energy was reflected back. The PVDF transducer picked up this signature signal and emitted back through the on-board antenna. The Vectronics® active antenna received this weak signal, amplified it and sent it to the data acquisition card for waveform display. The received waveform is shown in Figure 11.

The crack signal and the edge reflection signal after 25 times of averaging are clearly seen on the screen. From this preliminary experiment, the wireless inspection concept is proven to be viable, although the antennas were still close to each other (about 3 or 4 inches apart). When the transmission and receiving antennae moved farther in distance or not parallel to the on-board antenna, we got weaker signals. Several directions can be pursued in improving the signal to noise ratio or enlarge the antenna efficiency. For example, we could use a more powerful tone-burst generation source to increase the input energy; sensor efficiency could be improved by comb finger redesign and impedance matching; a more efficient on-board antenna and transmission antenna could be specially designed for 3 MHz etc.

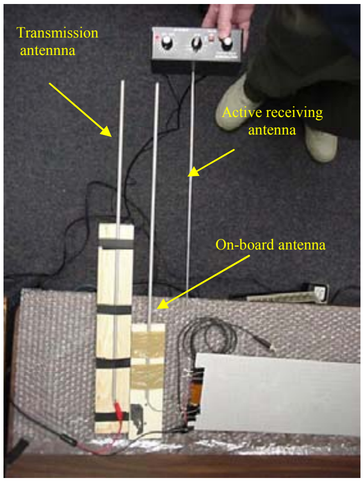


FIGURE 10 - Wireless inspection system setup

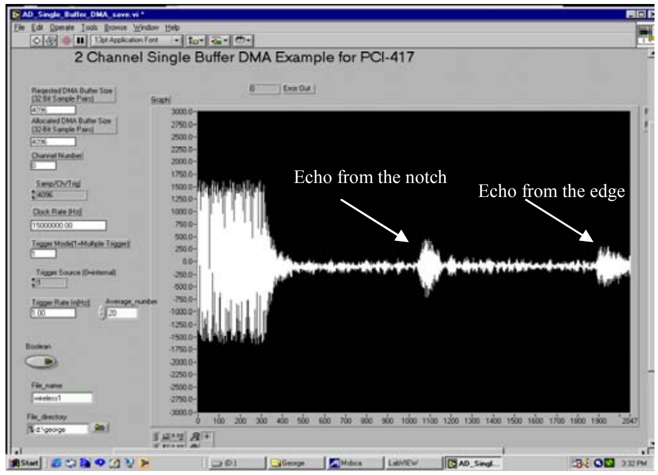
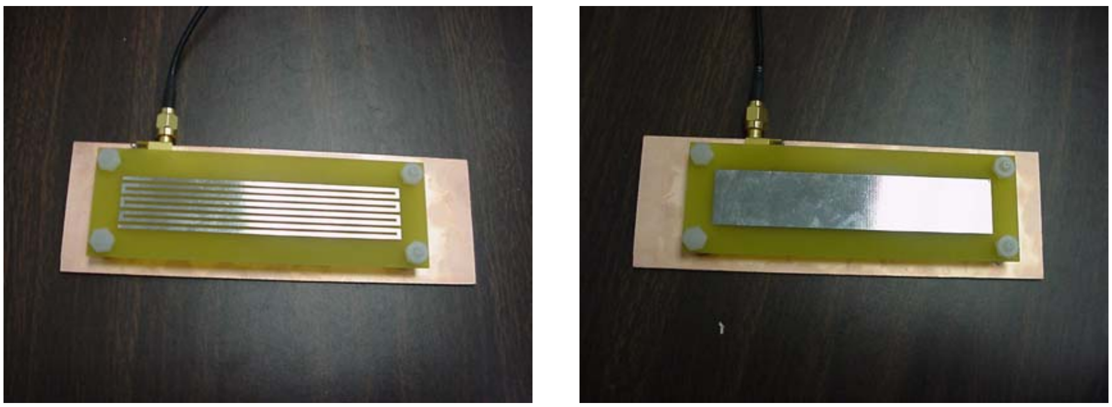


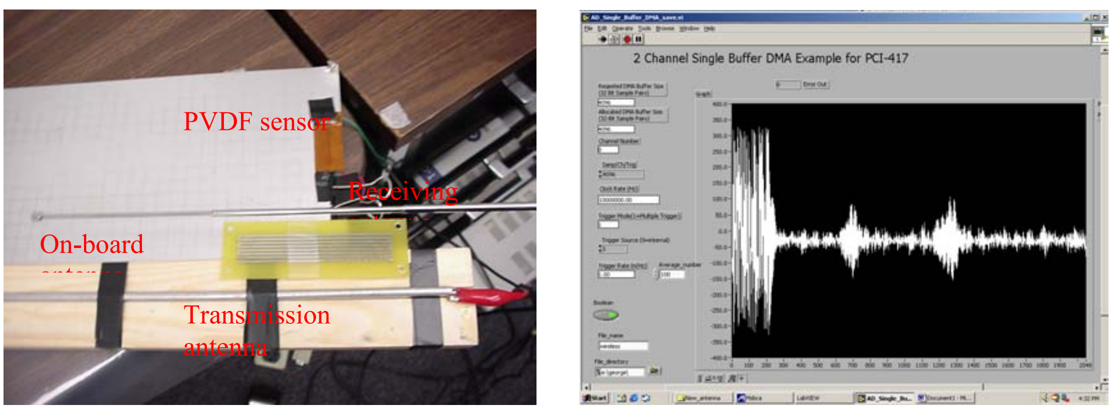
FIGURE 11 - Wireless inspection waveform of the of the 12mm long 50% through wall notch in a 0.8mm thick aluminium plate 26.5mm away from the sensor

<u>Small Flat Panel Antenna Progress</u>



(a) (b)

FIGURE 12 – (a) Small meander line 3 MHz antenna. (b) PIFA 3 MHz antenna. Area sizes of both are 10cm*2cm.



(a) (b)

FIGURE 13 – (a) Wireless inspection setup with small flat panel on board antenna; (b) Test result.

To make the on-board antenna more compact and conformal to the test structure, small flat panel antennae were designed and fabricated. Figure 12 shows two antenna designs, both of them are small (with area sizes 10cm*2cm.) and suppose to work at about 3 MHz. Figure 13 (a) shows a test setup for the crack detection in the aluminium plate, and Figure 13 (b) gives the recorded waveform. It is seen that crack signal is obvious.

Conclusions: This paper describes a prototype wireless guided wave NDE approach for aircraft wing inspection. The inspection system made use of a station monopole antenna as a transmitter, an on-board monopole or flat panel antenna as transponder, a PVDF comb transducer for guided wave generation and sensing, and a portable active monopole antenna for receiving. Preliminary experiments showed its feasibility for defect detection. Practical leave-on-board antenna designs for aircraft wing are discussed. Further improvements include a more powerful tone-burst generator for more input power; more efficiency sensor design and impedance matching; a more efficient on-board antenna and transmission antenna specially designed for 3 MHz etc.

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