17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

Wireless Ultrasonic Transducer Network for Structural Health Monitoring of an Aircraft Wing

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Abstract

A wireless, in-situ ultrasonic guided wave structural health monitoring (SHM) system has been developed and tested for aircraft wing inspection. It applies small, low cost and light weight piezoelectric (PZT) disc transducer network to the structural surface, and embeds a miniaturized diagnostic device for data collection and analysis. The whole system can be powered by an energy harvesting device such as an X-band microwave rectenna that converts illuminating microwave energy into DC. The collected data and processed results can be sent out wirelessly with a Zigbee radio. It showed good potential for crack and corrosion monitoring on complex panel structures such as an aircraft wing.

Keywords: PZT transducer network, Structural Health Monitoring, wireless, aircraft wing

1. Introduction

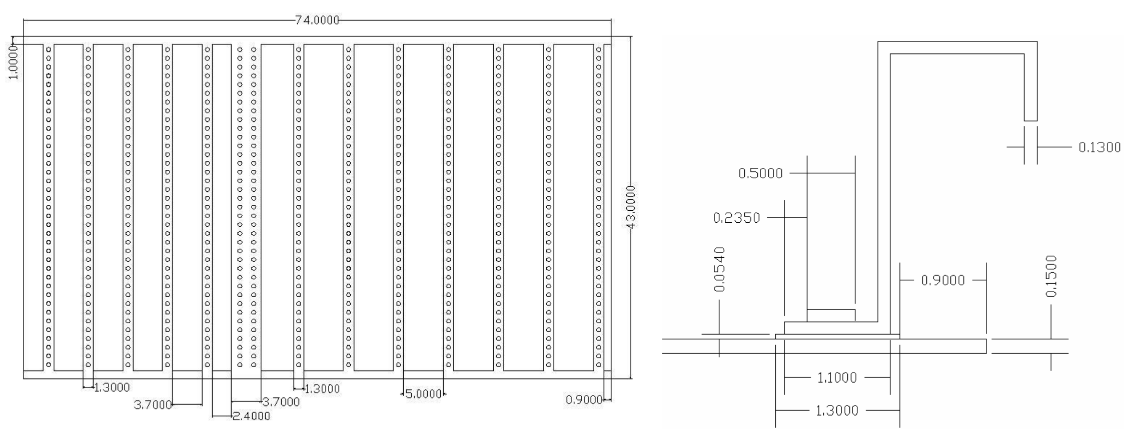
A significant number of civil and military aircraft have exceeded their designed lives. In 2000, 75% of US Air force aircrafts were more than 25 years old[1]. A major sustainment cost for these aging air vehicles is unscheduled maintenance. Structure health monitoring (SHM) technologies, by embedding smart sensors/actuators to the structures and responding/adapting to condition changes, can help transition from schedule-based maintenance to condition-based maintenance (CBM), thus increasing fleet availability and reducing the life cycle total ownership cost[2]. For example, inspection of a frequent structural problem or a defect-prone area (hot spots) at an inaccessible location desires a fast, low cost and reliable integrity monitoring system to ensure the safety and functionality of the structure. By embedding a SHM system into the structure to constantly monitor the hot spots and report collected data or diagnostic results wirelessly to a remote station, unnecessary scheduled maintenance can be minimized and defect occurrence can be detected early enough so that precaution can be taken before it is too late.

Many researchers have been developing or implementing wireless sensors or sensor networks for structural health monitoring applications. Straser and Kiremidjian[3] were among the first that proposed the integration of wireless communications with sensors based on a low-power 8-bit Motorola 68HC11 microcontroller. Lynch[4] has a good review article on various wireless sensors platforms for real-time health monitoring of civil structures. The Berkeley Mote Mica and Mica 2 are among the most popular platforms for implementing wireless sensor networks[5, 6]; however, it only operates in a passive mode and is limited in data sampling rate. Liu and Yuan [7] developed a high frequency Wireless Intelligent Sensor Platform (WISP) for ultrasonic applications, but they did not address the signal generation and circuit powering issues.

Ultrasonic Lamb waves have recently been widely used for SHM applications by embedding PZT ceramics or wafer sensors to the structures. A wireless means of interfacing with those guided wave sensor/actuators will greatly enhance their capability for SHM. In this paper, the concept of integrating wireless communications with sensors was adopted. A miniaturized diagnostic device with an on-board ultrasonic pulser and A/D converter was developed so that it can be embedded into the structure with the PZT arrays. The on-board pulser can generate 350 kHz, 70 V peak-to-peak tone-burst signal; a multiplexer made of mechanical relays and laser-diode switches was developed for multi-channel data acquisition; an 8-bit 10 Ms/s A/D chip was used for digitization; a microprocessor was used to process the data and a Zigbee module was used to send data wirelessly. To power the device wirelessly, a 10 GHz microwave rectenna was designed for converting microwave energy into DC. The rectenna can effectively deliver 100mW of DC power with 8 W of microwave power input into an illuminating horn antenna 0.6 meters away. The wireless system was tested with the PZT sensor array on an aircraft wing panel. It can effectively monitor a relatively large area for rivet cracks of size comparable to the wired inspection.

2. Embedded Ultrasonic Guided Wave Transducer Network

Aircraft wing panel is a complex structure. Figure 1(a) shows an example of a piece of E-2c surveillance wing panel and its rivet distribution. Those rivets are used to fasten the wing panel with its inner structures such as spars, ribs, and stiffeners. As shown in the figure, the rivet rows are at most 50 mm apart on the panel; within each row, the rivets are 8.8 mm apart. Figure 1(b) shows a detailed sketch of a stiffener fastened to the wing skin. The skin is not uniform in thickness. The section under the stiffeners is 0.5mm thicker than the rest of the panel. The wing panel is also painted with at least two layers of paints on the outer surface and one on the inner surface. All these structural properties cause strong wave scattering and attenuation when ultrasonic guided waves are used for defect inspection.



(a) (b)

Figure 1. Wing skin structure (a) overview of the rivet row sketch (b) typical geometry of a stiffener riveted to the skin (all the scales are in cm)

Figure 2. Eight element PZT array mounted on the wing panel. The image on the top right corner shows the transducer size compared with a coin.

A circular configuration of a PZT transducer network was implemented on the wing panel covering about 0.25 m in diameter. Figure 2 shows the example array. In this study, eight piezo-ceramic discs were attached to the inner surface evenly spaced. They took turns in generating ultrasonic signals while the others were listening. For example, when transducer 1 is sending a signal, transducers 2 to 8 are in a reception mode. After the guided wave data are collected by all the seven sensors, transducer 2 begins generating ultrasound and transducers 1, 3~8 are listening, and etc. Thus a total 56 sets of data can be collected this way.

3. Embedded Diagnosis Device Development

The diagram of our miniature ultrasonic diagnosis device developed is shown in Fig. 3. It is targeted to be embedded into the structure along with the transducer network for in-situ data acquisition and processing. The embedded SHM device has an on-board tone-burst pulser that can generate 350 kHz, 70 V peak-to-peak tone-burst signal, a multiplexed A/D board with a programmable gain amplifier for multi-channel data acquisition, a low- power-consumption microprocessor for circuit control and data processing, and a wireless module for transferring data and processed results. On the user side, a wireless receiver and a computer station can be setup to receive the wireless data from the embedded SHM device and perform any necessary data processing to display the results. In an ideal situation, an energy harvester would be integrated with the SHM device to collect ambient energy such as vibration or electromagnetic waves and convert them into electrical energy to power the embedded electronics and the sensor array. In this work, a microwave rectenna was developed [8] to convert X band microwave energy into DC. It was tested to be able to effectively deliver at least 100mW of power continuously with an 8W illuminating microwave source 0.6 meters away.

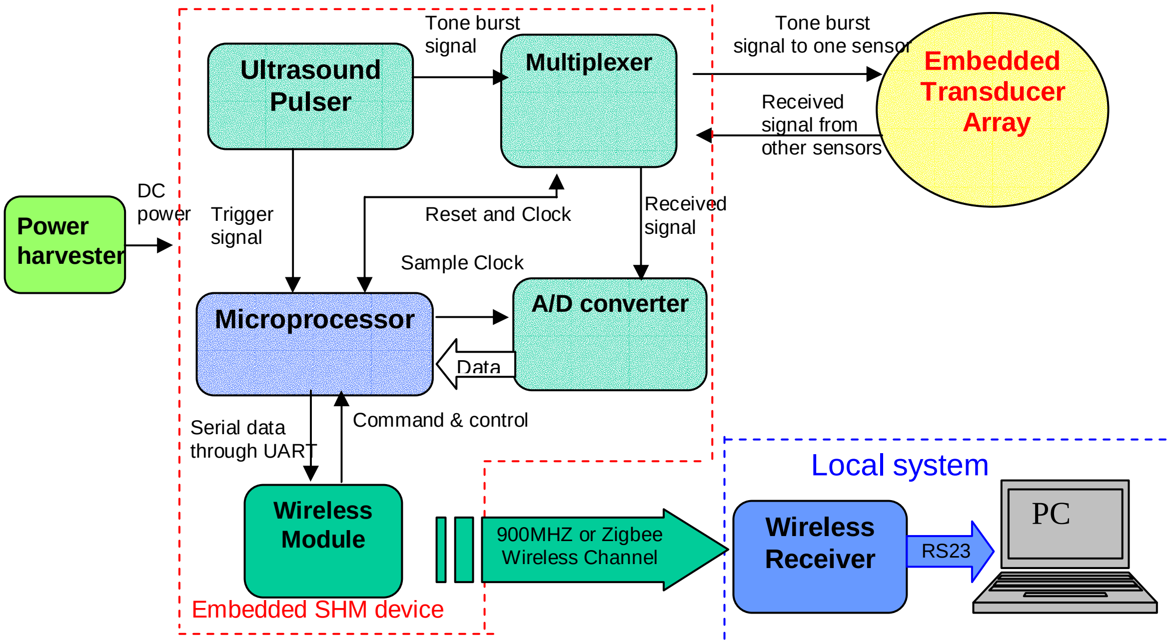


Figure 3. Diagram of the embedded ultrasonic structural health monitoring system

The ultrasonic pulser produced for the SHM system is designed based on a half-bridge series resonant inverter with an isolated output. It can generate 70 V peak-to-peak tone-burst pulses every 10 ms, with the center frequency tunable from 300 kHz to 400 kHz. Care was taken to select timing circuitry with very low standby current and fast start-up to meet the timing and limited power budget requirements. The design uses two timers: a low power, low frequency (TLC555) timer for the 10 ms pulse period and a high frequency (LTC6906) timer for pulsed converter operation. Additional circuitry is used to achieve fast dissipation of resonant energy and fast output shutdown at the end of each burst. The resonant frequency was chosen near the operating frequency as a compromise between circulating current losses and sensitivity to variations in the effective load capacitance. The total power consumption of the pulser is less than 30 mW for 0.2% duty cycle operation, which is up to 7~8 cycles of sinusoidal output per burst.

The interface of the SHM device with the on-board transducer network is done through a multiplexer and de-multiplexer (mux-demux) circuit so that each pair of the actuator/sensor elements can be interrogated. The mux-demux developed currently has 8x8 channel capability, but is expandable to 16x16 channels or more. It is made of low-power consumption mechanical relays to eliminate crosstalk problems found in solid state or laser diode switches. A drawback of the mechanical relays however is relatively high power consumption (~30mW) and slow response time (around 1ms for switching on/off). This is still tolerable in our application since channel switching is not frequent for pair-wise PZT data collection. The mux-demux can pass 200 V peak-to-peak ultrasonic signals and finish 56 sets of data collection for an eight-element sensor array within a minute. The A/D converter has 8-bits resolution and a 10MSPS sampling rate. It also has a programmable-gain amplifier so that signals from different channels can be compensated to the same amplitude level for fully utilizing the digitization resolution. The wireless modules used for data transfer is a Zigbee radio. Firmware communication scheme was developed to handle packet generation, scheduling and error detection and correction, etc. All the electronics boards, including the tone-burst pulser, the multiplexer, A/D converter, microprocessor, and the wireless module, were put into a metal box of 6.75”x4.75”x2” in dimension (see Fig. 5). It could be further miniaturized with careful circuit layout and boards integration.

Power to the device was achieved with an X-band microwave rectenna designed for converting microwave energy into DC power. The rectenna developed is shown in Fig. 4. The antenna elements are narrowband, linearly polarized patches for 10 GHz on a 0.25-mm thick Rogers Duroid substrate with a permittivity of 2.2. The gain of the patch calculated from its physical area is 1.39 (1.45dB). In each element, a rectifying diode is connected directly to the patch so that DC output is obtained with incident microwaves. The thin substrate allows the rectenna array to be flexible and conformal to the moderate curvature of an airframe while the desirable microwave properties are maintained. A single rectenna element at a 10mW/cm^2 incident RF power density has an output power of 5 mW with an estimated efficiency of 50%. The combination of 25 antenna elements in series achieves the total power of more than 100mW at an estimated efficiency of 40%.

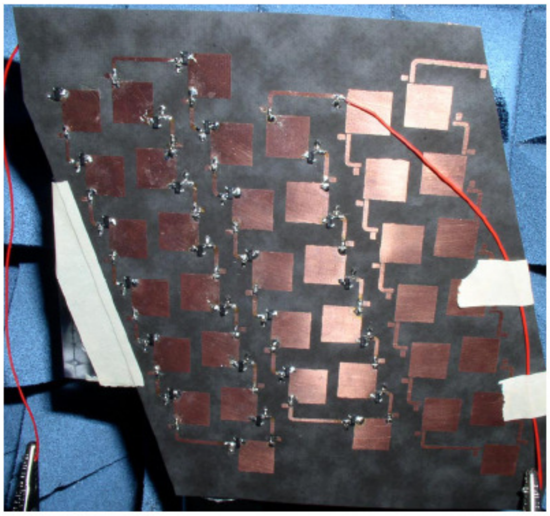


Figure 4. X-band microwave rectenna for wireless powering the on-board electronics

4. Experiment Results

The test setup for an aircraft wing panel inspection is shown in Fig. 5. An eight-element 350 kHz PZT transducer array was installed on the inner surface of the E-2 wing panel. The transducer input/output was connected to the embedded SHM device that can generate tone-burst signals and collect sensor data. With a LINX RF module and receiver device, the collected ultrasonic guided wave data was successfully received from the on-board SHM device. A near real-time data collection and display was achieved with a range about 5~10 meters in an office environment. Figure 6 shows example waveforms collected with the embedded device and with a direct wire connection, respectively. It is seen that the wireless waveform is almost identical with the wire-connected signal except at the very beginning where electromagnetic coupling effect is stronger than the wire-connection case.

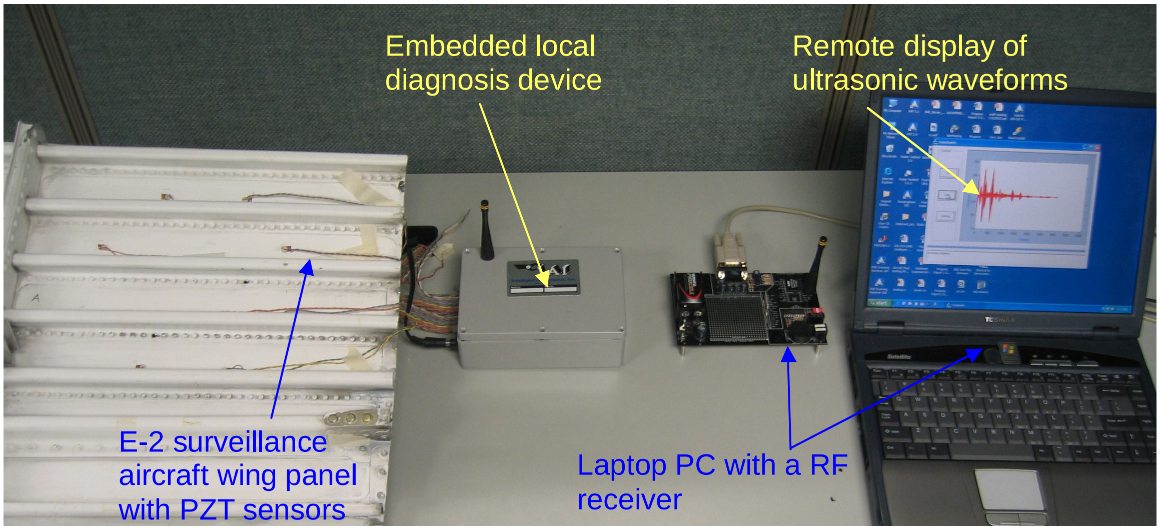
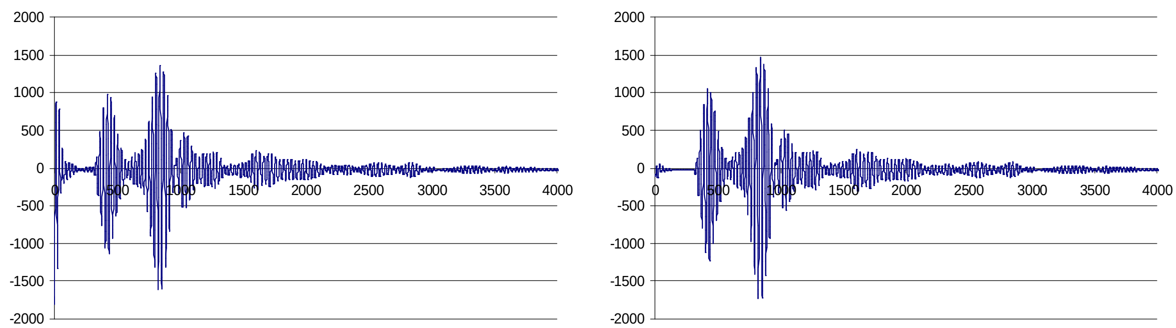


Figure 5. Embedded ultrasonic data acquisition and wireless transfer system for an E-2 wing panel inspection.

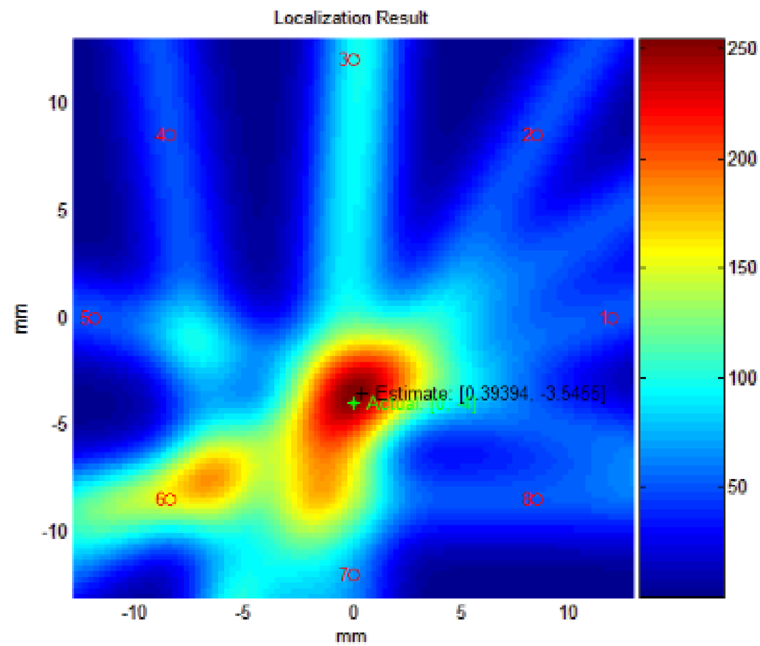


(a) Wireless waveform

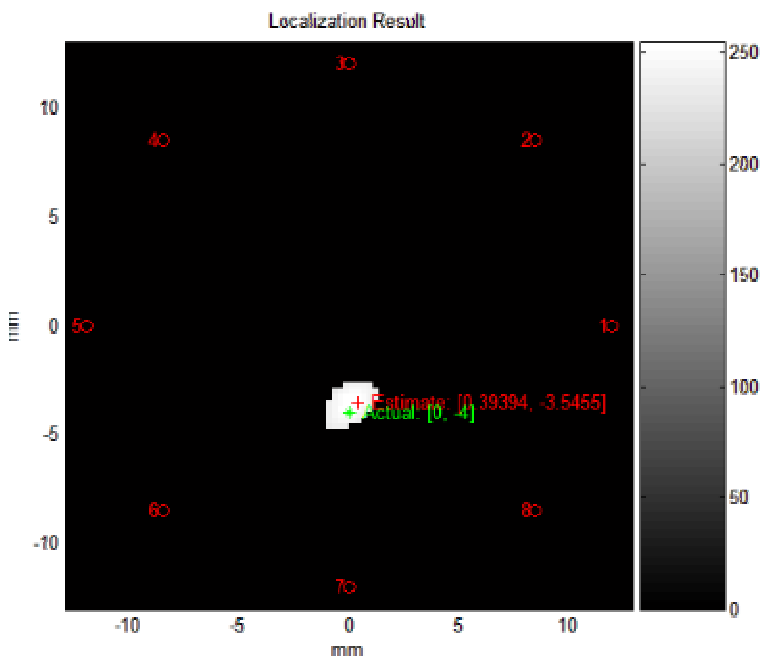
(b) Direct wire collected waveform

Figure 6. Comparison of ultrasonic guided wave data collected by (a) the wireless SHM device, and (b) the direct wire connected instrument.

After we collected reference data when there is no defect on the wing panel, we then drilled one rivet out and used the wireless SHM system to collect pair-wise PZT ultrasonic guided wave data for detect detection and localization. The data collected were transferred wirelessly to a laptop PC and processed with the RAPID algorithm developed previously [9]. Figure 7 shows the defect distribution probability map and the estimation result after applying a proper threshold to the probability density map. The estimated defect location agrees very well with the true location. This test proves the feasibility of using embedded PZT transducer network and diagnosis device for in–situ structural integrity monitoring of aircraft wings.



(a) Defect distribution probability map



(b) Defect location estimation

Figure 7. Defect detection and location estimation with the embedded ultrasonic data acquisition and wireless transfer system and RAPID algorithm [9]. (a) The defect probability density map for the loose rivet; (b) defect location estimation by setting a threshold to the probability density map.

5. Conclusions

The approach of using embedded ultrasonic guided wave transducer network and a wireless structural health monitoring device for aircraft wing inspection has been studied. The ultrasonic data can be collected on-board the wing and sent out wirelessly to a local PC. The signal quality is good and can be used for defect detection and localization. The use of Zigbee radio saves energy and can tolerate noise interferences. Power supply for the electronics and transducers can be achieved with an energy harvesting device such as a microwave rectenna. Experimental tests were carried out for a fully embedded system with PZT sensor array on the wing panel. Defect detection and location estimation are successfully demonstrated.

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