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DEVELOPMENT OF WIRELESS ULTRASONIC PROPAGATION IMAGING SYSTEM FOR IN-SITU AIRCRAFT INSPECTION

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ABSTRACT

Recently, laser ultrasonic propagation imaging (UPI) system has been greatly increased the attention of researchers for structural health management (SHM) application. The system has shown the promising results in the damage diagnosis of aircraft structures. However, the inspection was conducted in the experimental laboratory on a structure, which has been dissembled from an aircraft, which is not practical for the in-situ and large-scale aircraft structure inspection. This paper presents a wireless UPI system to realize the in-situ aircraft structure inspection. The system consists of a high-speed laser ultrasonic scanning system, a preamplifier-integrated piezoelectric (PZT) sensor network, an embedded wireless ultrasonic device (WUD), and a ground SHM system. In this work, four 8-channel analog multiplexers were used to connect the sensor nodes, which were installed along the webs of an aircraft, to the WUD with an integrated four-channel 12-bit analog-to-digital converter (ADC). The maximum sampling frequency of the ADC is 80 MHz. The WUD has an integrated Wi-Fi modem (802.11b/g/n). As further work, the UPI system will perform the inspection on a desired area with a selected local sensor node. Then, the acquired ultrasound will send to the ground SHM system to process for damage evaluation.

KEYWORDS : *laser ultrasonic, wireless sensing node, wireless-based data-acquisition, nondestructive evaluation, structural health management.*

1 INTRODUCTION

For the past decades, ultrasonic techniques have widely used for aircraft structure inspection [1]. In particular, laser based ultrasonic generation has been considered due to its advancement over a conventional piezoelectric (PZT) based ultrasonic transducer, with the high spatial resolution, the ability to inspect complex geometries, the non-contact in-situ ultrasonic generation at a low pulse energy, and the ability to remote inspection in hostile environment. Efforts have made to harness these advantages in the development of an ultrasonic propagation imaging (UPI) system [2-6]. Then, in the recent years, the UPI system incorporated with the damage evaluation techniques for SHM applications has been rapidly developed and the results showed great promise in enhancing the damage detection and evaluation of aircraft structures [7-10]. However, the inspection procedures were conducted in the experimental laboratory on the structure, which has been

dissembled from the aircraft. Consequently, the UPI system is not practical for the in-situ inspection on an aircraft.

In SHM applications, wireless sensing networks have become an attractive alternative to traditional wired sensor systems in order to reduce implementation costs of structural health monitoring systems. There are two wireless sensing paradigms, passive sensing and active sensing, used in the wireless sensing system. Then, the functional elements of the system can generally have their designs delineated into three or four functional subsystems: sensing interface, computational core, wireless transceiver and, for some, an actuation interface [11]. Recently, wireless active sensing have received attention as a promising monitoring technology due to its adaptability to incorporate with the well proven NDE monitoring tools including impact echo and ultrasonic wave testing. For an example, the wireless active sensing system employed piezoelectric pads and mounted the pads to the surface of structural plates. Then, the system commanded the piezoelectric pads to excite elements with Lamb waves, recorded the corresponding element responses, and interrogated the input—output response data for signs of crack damage. In the ultrasonic wave testing, the frequency range of the acquired ultrasound is normally wide, at least from few ten kilohertz to few megahertz. Thus, few megahertz sampling frequency has to be set in data acquisition device to satisfy the Nyquist theorem. Regards to this viewpoint, a data acquisition device with high sampling rate has to be appropriately selected when ultrasonic NDE technique is employed together with the wireless active sensing framework. However, wireless sensor networks present inherent challenges to performing traditional monitoring. To obtain high-throughput real-time data acquisition in the wireless sensing network is one of the challenges as due to the limited network resources, including power and communication bandwidth.

In this paper, a wireless ultrasonic propagation imaging system is presented to realize the in-situ aircraft structure inspection. The system consists of a high-speed laser ultrasonic scanning system, a preamplifier-integrated piezoelectric (PZT) sensor node, an embedded wireless ultrasonic device (WUD), and a ground SHM system. The development of the high-speed laser ultrasonic scanning system (< 4 kHz), the wireless ultrasonic device (WUD), and the preamplifier-integrated PZT sensor node will be discussed.

2 OVERVIEW OF WIRELESS ULTRASONIC PROPAGATION IMAGING SYSTEM

Figure 1 shows the overview of a wireless ultrasonic propagation imaging (UPI) system configuration on an aircraft. There are four main parts: a laser ultrasonic scanning system, a preamplifier-integrated PZT sensor node, embedded WUD, and a ground SHM system. The embedded WUD, which is installed inside an aircraft structure, is incorporated with the preamplifier-integrated PZT sensor network to allow the laser ultrasonic scanning system to inspection on all the aircraft structures. When the intended inspection area is determined, the corresponding local sensor node can be selected through the N-channel analog multiplexer of the embedded WUD that is controlled remotely by the computer of the ground SHM system through wireless link, as indicated in Fig. 1. In addition, the laser ultrasonic scanning system is controlled as well by the computer to perform the laser scanning process on the desired inspection area. In each laser impinging point, the corresponding ultrasonic signal generated is digitized in the DAQ board of the embedded WUD and sent back to the ground SHM system through the wireless access point (WAP) based on WiFi communication technique. At the WAP, the router used is wired to the ground SHM system through a network cable (RJ-45/Cat 5). This signal acquisition process will stop until the laser ultrasonic scanning process was completed. Lastly, the two-dimensional (2-D) spatial ultrasonic signals will be further processed for damage evaluation purpose.

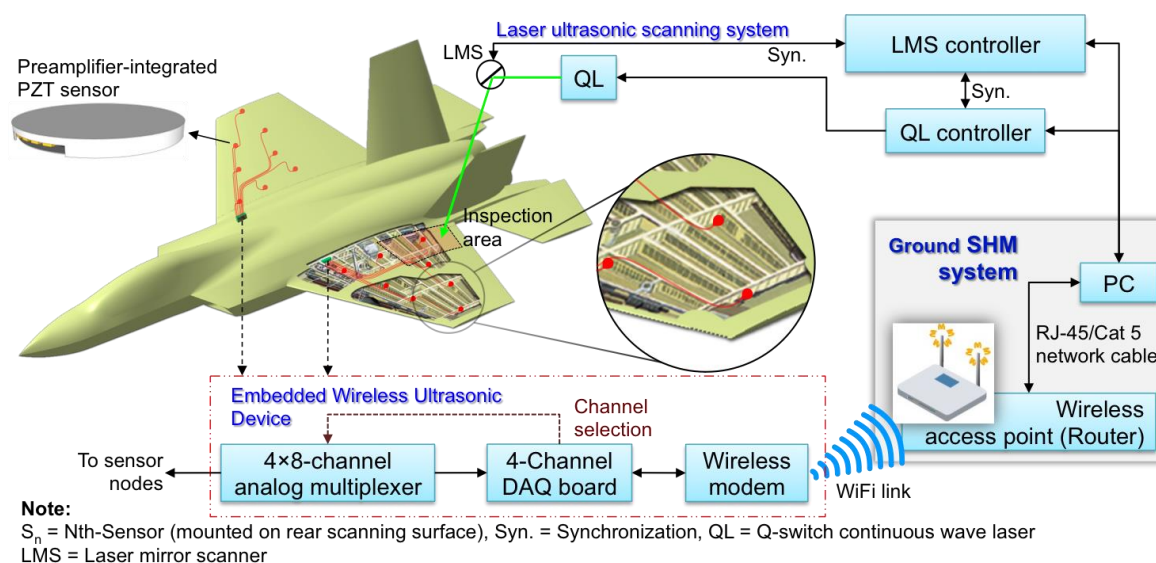


Figure 1: Overview of a wireless ultrasonic propagation imaging system configuration.

3 IMPLEMENTATION OF WIRELESS UPI SYSTEM

3.1 Laser ultrasonic scanning system

The laser ultrasonic scanning system introduced here was further improved from the previous laser ultrasonic scanning system [9]. Figure 1 shows the laser ultrasonic scanning system of a Q-switched continuous wave laser (QL), a laser mirror scanner (LMS), a LMS controller, and a computer with system operation software. The system operation software was realized in the LabVIEW platform and operated in the ground SHM system as shown in Fig. 1. The QL is a 532 nm laser with a pump source based on diode-pumped solid state (DPSS). The QL was selected and employed in this system because it has advancement over the flash lamp pulsed laser (PL). In addition, the QL shows good power stability and high pulse repetition frequency (PRF) as compared to PL. In general practice, it is essential to control the stability of the operating temperature of a QL to optimize its operation performance. The customized QL used in this report was also had the ability to work with the operating temperature of 0°C – 40°C. The specifications of the laser ultrasonic scanning system were summarized in Table 1.

Table 1: Laser ultrasonic scanning system specification.

| Specification | Performance |
|---|----------------------------------|
| Operating temperature | 0°C – 40°C |
| Laser scanning speed | 2000 mm/sec at $\Delta = 0.5$ mm |
| Three-dimensional Data mapping for movie generation (100 mm x 100 mm at $\Delta = 0.5$ mm) | Less than 20 s |

Besides the customized QL, LMS is also played an important role in the laser ultrasonic scanning system to allow the system to perform the raster scanning process. The LMS has two optical mirrors with working wavelength of 532 nm, and each is mounted on a galvanomotor. The laser fires laser optical pulses at the LMS through the laser beam entrance, and the mirrors of the LMS reflect the laser optical pulses toward the aircraft composite structure of interest. The galvanomotors are capable of rotating the mirrors rapidly within their optical angle range of $\pm 20^\circ$ through its two-axis galvanomotor driver board. The axes of rotation for the galvanomotors are orthogonal to each other.

The external driver card was used to replace the internal controller board used in previous study. The board enabled the real-time control of scan systems and lasers without requiring a computer due to its high-performance signal processor and extensive internal memory. Marking data (scanning pattern algorithm) can be loaded via a removable MMC memory card or by using the built-in USB 1.1 interface. The board consists of a connector to connect with the QL laser controller through a RS232 cable for synchronization purpose. Thus, the LMS can synchronize with the QL, which PRF set at 4 kHz, to maneuver the laser impinging point rapidly at the scanning rate of 4 kHz.

3.2 Preamplifier-integrated PZT sensor node

A preamplifier-integrated PZT sensor was developed with as shown in Fig. 3. The preamplifier-integrated PZT sensor consists of a 20 mm PZT ceramic element, a preamplifier module, and a sensor head design as indicated in Figs 3(a)-3(c), respectively. As indicated in Fig. 3(b), the preamplifier is designed using an amplifier IC (LM 392, SOIC package) and the gain can be expressed as below:

$$G = \frac{R_4 (R_1 + R_2)}{R_1 (R_3 + R_4)} \quad (1)$$

where, the R1 to R4 are the resistance. In this work, the resistances were set as shown in Fig. 3(b) and the gain was equalled to 5. The preamplifier circuit was also designed with the voltage level shifter, decoupling capacitor, and isolation resistance. The voltage level shifter was used to reduce the dual supply (+VDD/-VDD) to single supply (+ VDD) to reduce the size and cost of the circuit design. In this paper, the VDD was set to +3.6 V. The decoupling capacitor used in the circuit was to decouple voltage spikes on a power supply to reduce noise effect. Then isolation resistance used was to avoid instability caused by capacitive load. Figure 3(c) shows the integration of both sensor and preamplifier with a sensor head capsule, as made as a preamplifier-integrated PZT sensor node. The sensor node has designed the four output terminals, which are connected to the N-channel analog multiplexer, as indicated in Fig. 1, and power supply.

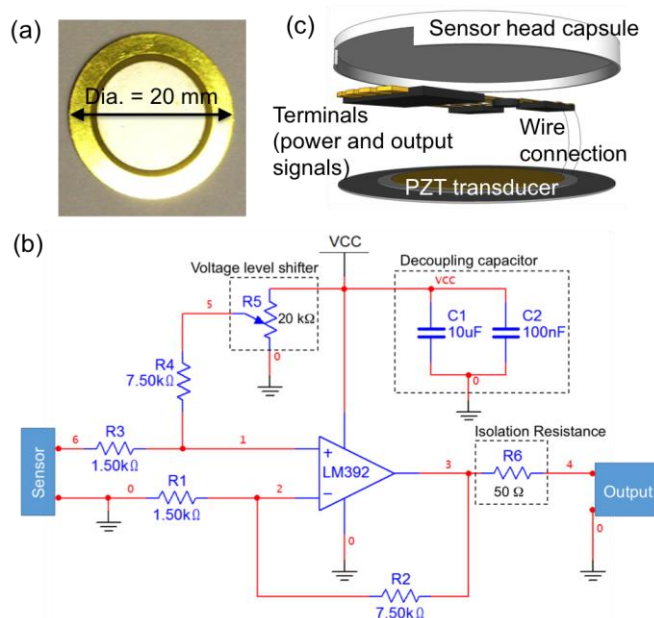


Figure 2 : Preamplifier-integrated PZT sensor node : (a) 20 mm PZT ceramic element, (b) preamplifier circuit design, and (c) sensor head capsule configuration.

3.3 Wireless ultrasonic devices (WUD)

Figure 3 shows the overview of the WUD configuration, which consists of 4×8-channel analog multiplexer, 4-channel DAQ board, and Wi-Fi modem. In this work, the four-channel ADC incorporated with 8-channel analog multiplexer (ADG608) was developed. Each WUD installed can have 32-channel sensing point distributed along the wing blade of an aircraft (Fig. 1) to facilitate the wireless UPI system to perform in-situ inspection. The WUD specifications are summarized as shown in Table 2. In 4-channel DAQ board, dual-core LPC4357 microcontroller, ARM Cortex-M4/M0, was considered as a controller of the WUD. The controller allows the computer of the ground SHM system to communicate and control remotely the WUD from the ground SHM system through the wireless link to perform the inspection exercise.

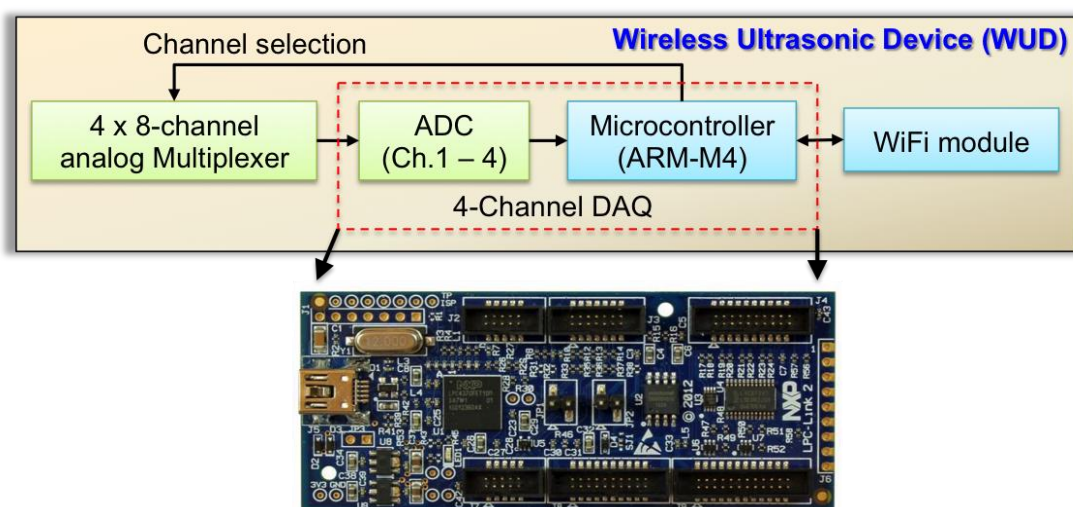


Figure 3: Overview of wireless ultrasonic devices (WUD) configuration.

Table 2: Wireless ultrasonic device (WUD) specifications.

| Specification | Performance |
|------------------|---|
| Processing speed | 204 MHz |
| Channels | 4 |
| Sampling rate | 80 MS/s |
| Resolution | 12-bit |
| Onboard Memory | 64 kB (ROM) ; 136 kB (SRAM) ; 1MB (Flash) |
| RF data rate | 802.11 b, g, n (1.4 MB/s, 6.8 MB/s, 8.4 MB/s) |

4 MEASUREMENT RESULTS AND DISCUSSION

Figure 4 shows the ultrasonic signal received at the preamplifier-integrated PZT sensor and the analog multiplexer. Both measurement results were obtained based on pencil-lead break test. Figure 4(a) shows the preamplifier (gain = 5) was successfully amplified the ultrasonic signal after received from the PZT ceramic element. Figure 4(b) shows the output signal of the analog multiplexer at one of the selected channel. The analog multiplexer shows the ability to send the selected input signal to its output terminal. The output signal shows exact replica of the input signal with no noise distortion.

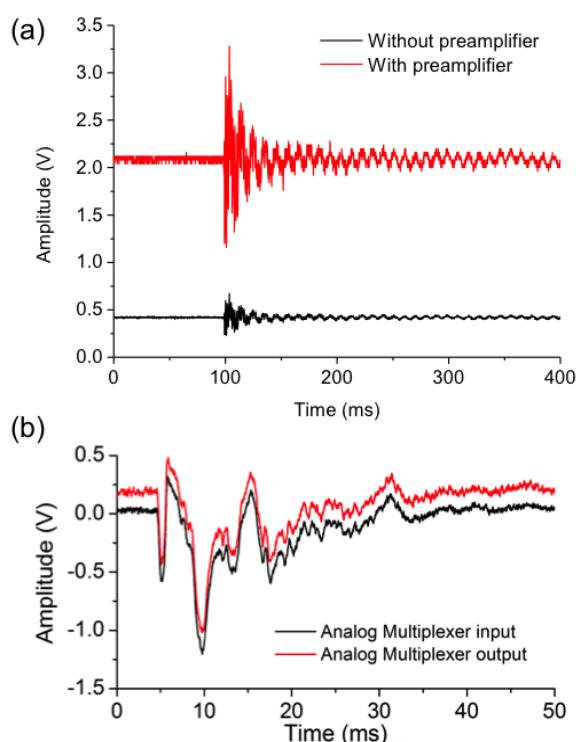


Figure 4: Ultrasonic signal received at (a) preamplifier-integrated PZT sensor node and (b) analog multiplexer.

5 SUMMARY AND FUTURE WORK

The wireless UPI system was proposed in this paper to realize the in-situ and large-scale aircraft inspection. The system was developed with a high-speed laser ultrasonic scanning system, a preamplifier-integrated PZT sensor network, an embedded WUD, and a ground SHM system. The WUD was developed with 4-channel 12-bit ADC which possessed of maximum 80 MHz sampling frequency. The preamplifier-integrated PZT sensor node and the analog multiplexer incorporated with microcontroller were tested. The results showed the sensor node was able received and amplified the ultrasonic signal. In addition, the analog multiplexer showed successfully output the selected input signal with no noise distortion. As for further work, the firmware of the WUD to control remotely the parameter settings of the ADC through the ground SHM system will be developed. Then, all the parts of the wireless UPI system will be integrated to perform the inspection on a target specimen.

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