Integrated SHM for aircraft wing and fuselage with built-in and mobile UPI systems in Smart Hangar

Hye-Jin SHIN 1, 2, Dae-Yun BAE 1, *Jung-Ryul LEE 2, 3

1 LANL-CBNU Engineering Institute-Korea, Chonbuk National University and 2 X-NDT Inc.
567 Baekje-daero, deokjin-gu, Jeonju-si, Jeollabuk-do 54896 Republic of Korea.
shinh0728@gmail.com, whitesmiledy@nate.com
3 Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, 305-338, Republic of Korea.
*Corresponding author: leejrr@kaist.ac.kr

Abstract

Materials such as aluminum alloys are widely used in aircraft structures. In the case of the use of Al-alloys in aircraft structures, fatigue cracks occur because of excessive and repeated loading and vibrations experienced during frequent flights. Ultrasonic propagation imaging (UPI) is a damage visualization technique that is used in structural inspections employing a laser scanning system and ultrasonic sensors. However, conventional UPI or other scanning systems, such as a scanning laser Doppler vibrometer, only permit a single area to be inspected at one time. It is also difficult to inspect inaccessible areas, such as the upper skins of the aircraft wings. In this work, we describe a multi-area scanning UPI system built in a hangar and a mobile UPI system with a serially connected piezoelectric sensor array that is able to rapidly scan at a maximum pulse repetition rate of 20 kHz. After acquiring the generated ultrasonic wave signal induced by laser excitation, UPI videos for the in-plate guided wave are displayed. Finally, internal damage can be identified in a damage visualization platform. The developed hanger-based multi-area scanning UPI system is demonstrated on wings of an actual aircraft containing back surface cracks. The multi-area scanning technique is enabled to simultaneous scanning by two synchronized laser mirror scanners. The multi-area scanning UPI system with tilting mirror systems installed in the hangar ceiling permitted a clear visualization of the damage. Meanwhile, the mobile UPI system also was demonstrated with a serially connected piezoelectric sensor array connected with conductive fabric tape to cover large scan area by using multiple PZT sensors. The serial-connected piezoelectric sensor network is installed on the skin of metallic aircraft fuselage side. The mobile UPI system with a serial-connected piezoelectric sensor network was allowed to confirm aircraft fuselage containing back surface cracks. The damage visualization results confirm that the proposed multi-area scanning UPI system, a mobile UPI system with a serially connected piezoelectric sensor array and their approaches have excellent applicability as a built-in UPI system and mobile UPI system for a Smart Hangar, which is a future SHM solution that will be used to realize a full-scale structural inspection.

Keywords: Actual aircraft SHM, Ultrasonic propagation imaging, In-situ non-destructive inspection, Smart Hangar, Serially connected piezoelectric net, Multi-time-frame ultrasonic energy mapping
1. INTRODUCTION

Materials such as aluminum alloys are widely used in aircraft structures. In the case of the use of Al-alloys in aircraft structures, fatigue cracks occur because of excessive and repeated loading and vibrations experienced during frequent flights. To detect metallic structures damage and defects in aircraft structures, visual inspection, tap testing, liquid dye penetrant inspection, ultrasonic testing, and so on, have been used as nondestructive inspection (NDI) techniques. However, these NDI techniques have some limitations in terms of accuracy of damage detection, accessibility of inspection personnel and possible inspection speed for large composite structures, such as in-service aircraft [1]. Ultrasonic propagation imaging (UPI) is a damage visualization technique that is performed using a non-contacting laser scanning system and contact/noncontact/wireless ultrasonic sensors. This technique displays video results on ultrasonic wave propagation and image results processed in the time, frequency, and wavenumber domains for any damage. The UPI technique has many advantages, such as rapid inspection speed, non-contacting scanning, and quantitative damage localization and evaluation. Furthermore, long range operations at a few tens of meters is possible by collimating the excitation laser beam, allowing the inspection of in-service large scale composite structures, which are difficult to access by inspectors [2]. In this work, we describe a multi-area scanning UPI system built in a hangar and a mobile UPI system with a serially connected piezoelectric sensor array.

2. DEMONSTRATION OF A MULTI-AREA SCANNING UPI SYSTEM BUILT INTO A HANGAR FOR ACTUAL AIRCRAFT INSPECTIONS

The multi-area scanning UPI system built into a Hangar is one of applications of the UPI system, extended to multi-area simultaneous inspection by adding a beam expander, a laser mirror scanner and a beam splitter at long distance and is also able to inspect inaccessible area of large-scale structures such as upper skin of huge aircraft using built-in tilting mirror systems which adjusts direction of scanning laser beam on the target. By combination of these UPI techniques, the Smart Hangar system facilitates the full-scale inspection for in-service aircraft. The UPI system is able to rapidly scan at a maximum pulse repetition rate of 20 kHz. After acquiring the generated ultrasonic wave signal induced by laser excitation, UPI videos for the in-plate guided wave are displayed. Finally, internal damage can be identified in a damage visualization platform.

To verify the applicability of a multi-area scanning UPI system in a hangar, a demonstration was performed using an actual aircraft. As shown in Figure 1, the multi-area scanning UPI system was installed on the second floor of a hangar-like laboratory to demonstrate the built-in UPI concept of a Smart Hangar. Two tilting mirror systems were installed on the ceiling of the hangar and used to move the scanning area. The distances from the multi-area scanning UPI system to the two tilting mirror systems were 7 m and 10 m. The distance from each tilting mirror system to the upper skin of the airplane was 4 m. The airplane skin was composed of an Al-alloy with a painted outer surface (Epoxy/Acrylate lacquer). The total thickness of the skin was 0.5 mm. The skin of the main wing contained artificial back surface cracks, which were made carefully by an office cutter, with the following dimensions: length of 10 mm, width of 1 mm and depth of 0.3 mm.
The single scan area was 200 mm × 200 mm, and the scan interval was 0.5 mm. Ultrasonic waves generated by the impinging laser beam pulses were guided in the skin and captured by the amp-integrated PZT sensors and were filtered using a 300-500 kHz band-pass filter. The multi-area scanning UPI system has the advantage of being able to rapidly inspect target structures using the high-speed LMS with a maximum PRF of 20 kHz. However, in low damping materials, such as metals, reverberation occurs as the PRF is increased [3, 4]. Residual waves caused by the reverberation effect act as noise during signal processing. In this work, for the painted Al-alloy skin on the commercial aircraft tested in the hanger, we performed the damage visualization experiment depend on PRFs to determine the optimal results in terms of the trade-off between damage detectability and scanning time. Figure 3 (a) shows the ultrasonic propagation imaging (UWPI) result for a PRF of 1 kHz over the inspection area on the right side wing, as shown in Figure 2. This result shows scattering waves induced by the back surface crack, but no reverberation effect. As shown in Figures 3 (a)-(c) and (e)-(g) with PRFs of 1 kHz, and 3 kHz, the UWPI and ultrasonic energy mapping
(UEM) also show the damage location and scattering waves are induced by the crack [5, 6, 7, 8]. However, the reverberation effect becomes more serious as the PRF is increased. Residual waves induced from the previous scanning point were also found around the crack on the UEM result for the same energy mapping parameters. In cases of PRF of 4 kHz and 5 kHz, the location and shape of damage could not be identified because of the strong reverberation effect, as shown in Figures 3 (d) and (h). At the same time, the inspection results for the left side wing were obtained at PRFs of 1 kHz, 3 kHz, 4 kHz and 5 kHz for the scan area, as shown in Fig. 4.

Figure 2: Scan area on the right wing (stand-off distance of the laser beam: 11 m).

Figure 3: Damage visualization results for the right wing: (a) UWPI (1 kHz PRF), (b) UWPI (3 kHz PRF), (c) UWPI (4 kHz PRF), and (d) UWPI (5 kHz PRF), (e) UEM (1 kHz PRF), (f) UEM (3 kHz PRF), (g) UEM (4 kHz PRF) and (h) UEM (5 kHz PRF).
First, the inspection was performed at a PRF of 1 kHz. The UWPI and UEM results show the damage locations and scattering waves induced by the crack damage at two locations in the inspection area, as shown in Figures 5 (a) and (e). Additionally, the UWPI and UEM results at PRFs of 3 kHz and 4 kHz still successfully show the damage locations and scattering waves induced by the crack damage, as shown in Figures 5 (b), (c), (f) and (g). However, for PRFs of 5 kHz (Figs. 5 (d) and (h)), it was impossible to identify the damage locations and scattering waves. Consequently, the PRF for the simultaneous inspection of the painted skins of the metallic airplane wings could be chosen as 3 kHz.

![Figure 4: Scan area on the left wing (stand-off distance of the laser beam: 14 m).](image)

![Figure 5: Damage visualization results for the left wing: (a) UWPI (1 kHz PRF), (b) UWPI (3 kHz PRF), (c) UWPI (4 kHz PRF), (d) UWPI (5 kHz PRF), (e) UEM (1 kHz PRF), (f) UEM (3 kHz PRF), (g) UEM (4 kHz PRF) and (h) UEM (5 kHz PRF).](image)
4. IMPLEMENTATION OF THE MOBILE ULTRASONIC PROPAGATION IMAGING SYSTEM WITH SERIALLY CONNECTED PZT SENSOR NET

A single PZT sensor stimulated by the UPI system is suitable for detection of cracks at hotspots, this method has limited coverage in large regions of complex structures such as an aircraft fuselage. This is because the dispersive ultrasound is reflected from the discontinuity of edges and attenuated by the increasing propagation distance [17]. To monitor large and complex geometries of an aircraft fuselage, the mobile UPI system was demonstrated with a serially connected piezoelectric sensor array connected with conductive fabric tape to cover large scan area by using multiple PZT sensors. Figure 6 (a) shows the SHM target area in the Cessna-150 fuselage where three PZT sensors were installed for the serially connected PZT sensor net. The distance between the two adjacent sensors was 300 mm, and the scan area was 900 mm × 200 mm. Figure 6 (b) presents the serially connected PZT sensor array installed on the back surface of the fuselage skin. The weight increase due to this sensor net was merely 4.6 g (2.4 g for the three PZTs and 2.2 g for the lead tape). The lead tape was composed of the conductive fabric tape and the insulation tape. The insulation tape was used to separate the connection from the fuselage skin because the conductive fabric tape possesses double-sided conductivity. The targeted fuselage skin encompassed artificial cracks, and their locations are presented in Fig. 7 (a). Cracks A and B were copied from tear cracking on the fuselage back surface skin, and cracks C to E were copied from fatigue crack

![Figure 6: (a) Locations of sensor and scan area on the front surface, and (b) serially connected sensor array on the back surface of the fuselage skin.](image-url)
propagation initiated from the rivet holes in the lap joints as indicated in Fig.7(b). The depth of each hidden crack was 0.3 mm from the back surface, which was generated by an office cutter. The targeted fuselage skin was inspected using the UPI system with PRR of 200 Hz at a laser pulse scanning interval of 0.5 mm. The scanning laser head of the UPI system was placed 2.0 m from the inspection surface, and the laser energy was set to 1.27 mJ. The acquired ultrasounds were bandpass-filtered through an inline filter ranging from 5 to 180 kHz. Figure 8 (a) shows the inspection results captured from the multi-source UWPI result.

![Figure 7](image.png)

**Figure 7:** (a) Locations of damage and scan area on the front surface and types of damage on the back surface.

![Figure 8](image.png)

**Figure 8:** UWPI freeze frames (a) at t = 16.0 μs in overall scan area, (b) at t = 21.6 μs in damage A, (c) at t = 21.6 μs in damage B, (d) at t = 27.2 μs in damage E, (e) at t = 37.6 μs in damage C, (f) at t = 37.6 μs in damage D, and (g) 66.4 μs in damage C.
Figure 9: Single-time-frame ultrasonic energy mapping with source removal technique (a) at 21.6μs for the scattering waves generated from cracks A and B, (b) at 37.6μs for the scattering waves generated from cracks C and D, (c) at 27.2μs for the scattering wave generated from crack E, and (d) at 66.4μs for the reflection wave-induced scattering wave generated from crack C to enhance the wave energy for crack C, (e) multi-time frame ultrasonic energy map combined single-time frame ultrasonic energy maps.

All cracks listed in Fig. 7 (b) were successfully detected by the scattering waves as enlarged in Figs. 8 (b) to (g). To visualize all cracks in the overall scan area of 900 mm × 200 mm (Fig. 7 (a)), the multi-time-frame UEM (mUEM) with the source removal technique was executed based on the information of Figs. 8 (b) to (g). The conventional UEM algorithm [5, 6, 7, 8] using a single time frame is not appropriate for visualization of all of the cracks, but proposed mUEM algorithm is able to visualize all of cracks by averaging the single-time-frame UEMs. The mUEM presented in Fig. 12 was obtained by averaging Figs. 11(a) to (d)). This image
processing procedure is far easier for cracks perception because the locations of each cracks can be immediately distinguished from the surrounding area in a single-frame map with their own colors or shapes.

9. CONCLUSIONS

In this work, we proposed a multi-area scanning UPI system built in a hangar and a mobile UPI system with a serially connected piezoelectric sensor array. The developed hanger-based multi-area scanning UPI system was demonstrated on wings of an actual aircraft containing back surface cracks. The multi-area scanning UPI system with tilting mirror systems installed in the hangar ceiling permitted a clear visualization of the damage. The multi-area scanning UPI system was modified by adding long-range scanning and moving capabilities by installing the tilting mirror systems on the hangar ceiling. The simultaneous inspection of both painted skins of the left and right metallic airplane wings was successfully demonstrated by identifying the back surface cracks at a PRF of 3 kHz. Consequently, this work has proven that this new expansion from a conventional UPI system will play an important role in realizing a full-scale automatic structural inspection and the Smart Hangar concept. Meanwhile, the mobile UPI system was also demonstrated with a serially connected multiple PZTs connected with conductive fabric tape to cover large scan area. The serial-connected piezoelectric sensor network is installed on the skin of metallic aircraft fuselage side. The mobile UPI system with a serial-connected piezoelectric sensor network was allowed to confirm aircraft fuselage containing back surface cracks. The damage visualization results confirm that the proposed multi-area scanning UPI system, a mobile UPI system with a serially connected piezoelectric sensor array and their approaches have excellent applicability as a built-in UPI system and mobile UPI system for a Smart Hangar, which is a future SHM solution that will be used to realize full-scale aircraft structural inspection or similar large structures.

9. ACKNOWLEDGEMENTS

This paper was supported by the Leading Foreign Research Institute Recruitment Program (2011-0030065) and Development of the Composite Lattice Structure (15-CM-MA-12) through the National Research Foundation of Korea funded by the Ministry of Science, ICT and Future Planning.

REFERENCES


