Triple Functional UPI (Ultrasonic Wave Propagation Imager) and Applications to Aircraft

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ABSTRACT

As a fast nondestructive inspection (NDI) system, triple functional ultrasonic wave propagation imager (UPI) was developed. It features three modes: Q-switched laser scan guided UPI (QL-scan G-UPI), angular pulse-echo UPI (A PE UPI), and laser Doppler vibrometer scan guided UPI (LDV-scan G-UPI). QL-scan G-UPI utilizes Lamb waves created by the Q-switched laser, with a PZT sensor receiving waves distorted by structural damage. A PE UPI employs bulk waves induced by the same laser, and the LDV captures bulk waves reflected from the back face or internal defects in the thickness direction. LDV-scan G-UPI uses standing waves generated by a PZT exciter, which are captured by the same LDV used in the A PE UPI. By employing acoustic wavenumber spectroscopy (AWS), the thickness changes in structures due to damage can be identified through the calculated wavenumber of the standing waves. A significant advantage of this equipment is its inspection speed. The maximum scanning speeds of each mode are 32.11 m^2/h for A PE UPI, 23.21 m^2/h for QL-scan G-UPI, and 28.35 m^2/h for LDV-scan G-UPI, respectively. The scanning speed can be adjusted based on the required precision of the damage detection, as smaller scan intervals are required to detect minute internal damage. The post processing algorithms for diagnosing structures in this equipment are variable time window amplitude mapping (VTWAM), ultrasonic energy mapping (UEM) and AWS. It takes less than one minute to visualize the results for a 1 x 1 m^2 plate. The current equipment was evaluated by detecting various types of damage in aircraft structures. The detected damage includes cracks and corrosions in aluminum structures, as well as film inserts, debonding and delamination in composite structures. In particular, damage growth in a composite plate during fatigue tests, and debonding between rivets in an aircraft were successfully detected using A PE UPI without any disassembly or interference.

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INTRODUCTION

The aerospace industry has undergone a significant change with the increasing usage of carbon fiber reinforced plastic (CFRP) composites in the main structures of both aircraft and unmanned aerial vehicles (UAVs). This shift is driven by the exceptional strength-to-weight ratio, corrosion resistance, and design flexibility offered by CFRP materials, which enable the development of lighter, more fuel-efficient, and high-performance aircraft. As a result, modern aircraft incorporate a substantial proportion of CFRP structures in their fuselage, wings, and other critical components. Similarly, the UAV sector is witnessing a surge in CFRP usage to enhance endurance, payload capacity, and overall operational capabilities.

However, the complex nature of CFRP materials and their manufacturing processes introduces unique challenges in ensuring structural integrity and safety. Unlike traditional metallic materials, CFRP composites are susceptible to various forms of defects, including delamination, debonding, porosity, fiber misalignment, and impact damage, which can significantly degrade their mechanical properties. These defects, whether occurring during manufacturing, service operation, or maintenance, can significantly compromise mechanical performance. Consequently, the increasing prevalence of CFRP structures in aerospace applications has heightened the importance of nondestructive inspection (NDI) techniques. NDI methods play a pivotal role in detecting and characterizing defects in CFRP components without causing damage to the materials. This enables timely maintenance and repair actions, ensuring the continued airworthiness and reliability of aircraft and UAVs. Additionally, the increasing usage of composite structures has led to an increase in the downtime required for NDI. This is due to the complexity of composite materials, which makes visual inspection for damage detection difficult. Therefore, there is a need in the aerospace industry to develop high-speed NDI technologies to reduce inspection time and downtime.

In response to this need, this study presents the development of a triple functional ultrasonic wave propagation imager (TUPI) - a novel, fast NDI system capable of efficiently detecting various types of damage in aerospace structures. The TUPI system integrates three operational modes: (1) Q-switched laser scan guided UPI (QL-scan G-UPI) [1], (2) angular pulse-echo UPI (A PE UPI) [2], and (3) laser Doppler vibrometer scan guided UPI (LDV-scan G-UPI) [3]. Using these modes, the system successfully identified a range of artificial and real defects in both metallic and composite aerospace components. This paper is organized as follows. Section 2 describes the TUPI system and the damage detection algorithms applied to each operational mode. Section 3 presents experimental results from inspections of both artificial and real defects, including debonding detected in a UAV structure. The paper ends with the conclusions.

TRIPLE FUNCTIONAL UPI

Figure 1 illustrates the TUPI system. The main components located in the system head (shown on the left one in Figure 1) are a Q-switched laser with a wavelength of 1064 nm and an LDV with a wavelength of 1550 nm for generating and sensing laser ultrasonic waves. There are a PZT sensor and a PZT actuator which are attached to the surface of the structure and connected to the controller (the right one of Figure 1). In the controller, there are a 4-channel data acquisition unit, a signal conditioner, a 40 MHz function generator, and an amplifier. The system can operate in the aircraft hangar within the temperature range of -10 ℃ to 40 ℃.

Figure 1. Triple functional UPI system.

The three modes of TUPI shown in Figure 2 are the QL-scan G-UPI, A PE UPI, and LDV-scan G-UPI. This system provides fast inspection capabilities. When the inspection is performed with a 1 mm interval, the speeds of QL-scan G-UPI, A PE UPI and LDV-scan G-UPI are 23.21 m^2/h, 32.11 m^2/h, and 28.35 m^2/h, respectively. This system also provides damage visualization. QL-scan G-UPI can visualize the propagation of ultrasound wave field over the inspection area and A PE UPI is able to visualize longitudinal wave propagation through the thickness. Wave propagation allows users to infer damage by identifying changes in the wavefield pattern.

QL-scan G-UPI uses Lamb waves created by the Q-switched laser. The waves are generated by directing a pulsed laser beam toward the sampling grid points, one after another, in the scan area. Each laser pulse carries about 2 mJ of energy and, once absorbed by structure, ultrasonic waves propagate away from the laser impingement point. The laser beam is passed through a galvanometer-based laser mirror scanner (LMS) in the system head to the target structure. The LMS has two mirrors which are connected to Galvano-motors, and the rotation axes are orthogonal to each other. The Lamb waves are captured using a PZT sensor affixed to the structure. This mode moves the ultrasound source from point to point in a raster scan pattern. By manipulating the sensing data, it is possible to create the visualization of an animated wavefield (guided wave UWPI video) that propagates outward from the PZT sensor, as shown in the upper one of Figure 3. The mapping of energy values, named as ultrasonic energy mapping (UEM) [1], was used for damage detection.

Secondly, A PE UPI consists of the QL, the LDV, and the LMS, as shown in Figure 2. The maximum excitation frequency of the QL is 10 kHz, and the maximum sampling rate of the LDV is 80 MHz. Both the sensing beam and the generation beams are combined using optics to obtain the pulse-echo through-the-thickness ultrasonic information at each point in the inspection area. The combined beam, which passes through the LMS, scans the inspection area in a raster scan pattern. And the LDV beam can detect the pulse-echo wave (bulk wave) in the thickness direction. These pulse-echo waves are collected for the scan area, and by manipulating the sensing data, it is possible to generate the pulse-echo ultrasonic wave propagation video shown in the mid one of Figure 3. The intensity map of the video for the scan area is similar to a C-scan image. The variable time window amplitude mapping (VTWAM) [2] method was used to visualize the damage.

Lastly, LDV-scan G-UPI consists of the LDV, the LMS, and a PZT actuator shown in Figure 2. The PZT transducer excites the structure with a standing wave, and the LDV measures full wave field, as shown in the lower one of Figure 3. In this mode the extraction of time-invariant wavenumber characteristics is employed. This mode can extract the wavenumber components that have been altered due to defects caused by thickness changes. This is acoustic wavenumber spectroscopy developed by Flynn et al. [4]. Wavenumber mapping in spatial domain was used to visualize damage in this mode.

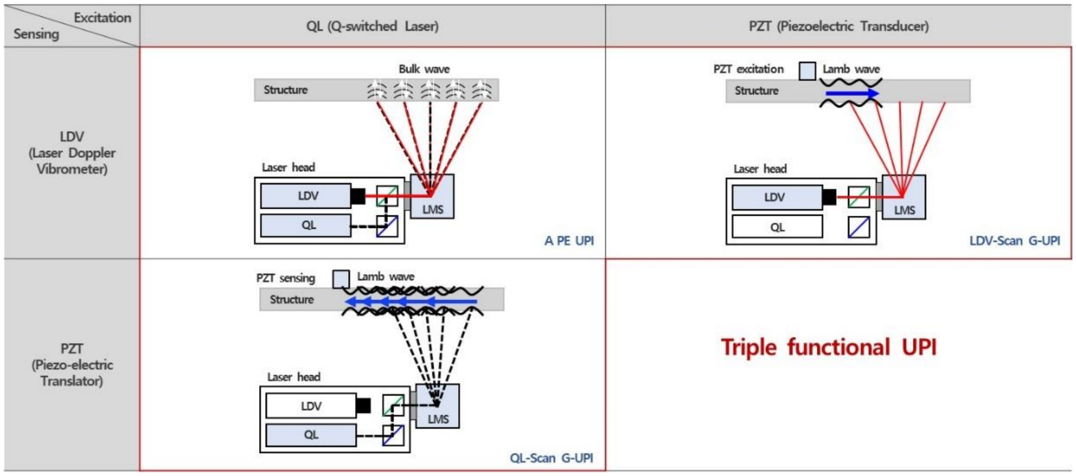

Figure 2. The concept and three modes of the system.

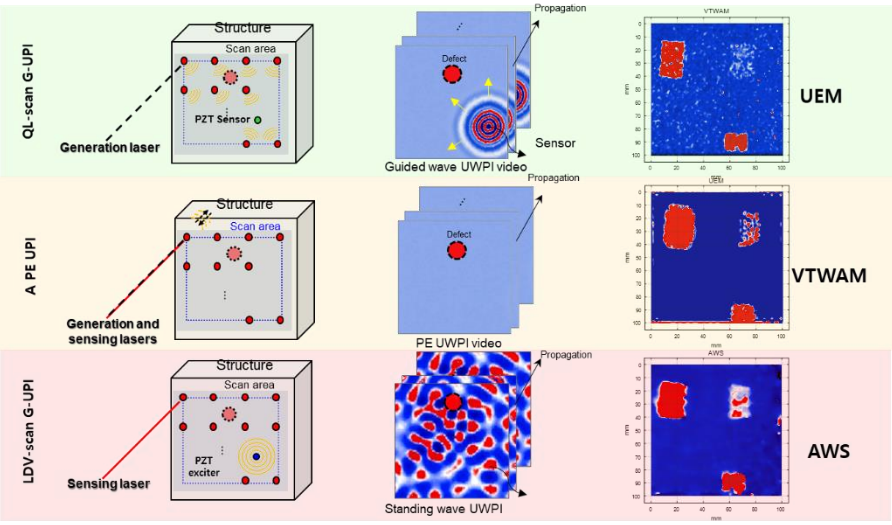

Figure 3. The inspection methods and damage detection algorithms of the system.

APPLICATIONS

The effectiveness of TUPI system in nondestructive inspection applications was experimentally verified by applying this system for various kinds of artificial and real damage. For the artificial damage, an aluminum plate with a thickness of 2 mm and a composite plate with 16 carbon UD plies (approximately 2 mm thickness) were used. The aluminum plate contained 12 artificial cracks of 4 different sizes (ranging from 5 mm to 20 mm) at 3 different thickness locations (ranging from 0.5mm to 1.5 mm). The composite plate had 12 artificial delaminations of 4 difference sizes (ranging from 5 x 5 mm to 20 x 20 mm) at 3 different thickness locations (ranging from 0.5mm to 1.5 mm), that were made by placing a specific size film insert. We also fabricated a small composite wing with 16 artificial delaminations (film insets) of 4 difference sizes at 4 different thickness locations. Pseudo-corrosion defects in small aluminum plates were also tested. Using salt water, we created 4 different sizes of corrosion defects (ranging from Ø5 mm to Ø20 mm) on other aluminum plates. For the artificial defects, 5 mm cracks, 5 x 5 mm film inserts, and Ø5 mm corrosion were successfully detected. By detecting various kinds of defects, it was found that LDV-scan G-UPI is sensitive to defects in metal structures and QL-scan G-UPI is effective at detecting defects in composite structures. A PE UPI is useful for precisely quantifying defects after the previous two modes identify damage. This mode exhibits good precision in damage size estimation for flat structures in local areas. However, A PE UPI is not recommended when the inspection plane of the structure has a slope greater than 5 degrees, as damage detection may be inaccurate in this condition.

Recently, we conducted compression fatigue tests of composite plates with low-velocity impact damage. The fatigue test was set up in accordance with ASTM D7137 [5], and the specimens were supported with the ASTM standard fixture. During the test, the growth of delamination in the plate was inspected with A PE UPI, which did not need specimen to be disassembled from the test setup for inspection because it is a fully non-contact NDI method. A PE UPI was also used for the inspection of a real UAV composite wing. Figure 4 shows the inspection setup and results. VTWAM results show the debonding boundaries and 5 rivets. These rivets were installed to prevent debonding growth.

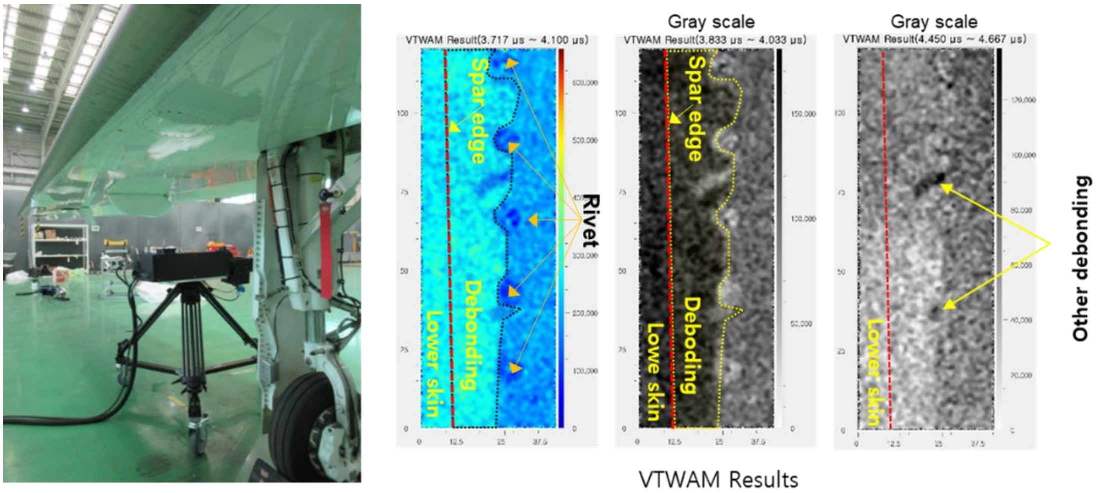

Figure 4. The inspection setup and results of UAV composite wing

CONCLUSIONS

Triple functional UPI system has been developed for damage detection in various aircraft structures. QL-scan G-UPI, A PE UPI and LDV-scan G-UPI are the three modes of this system, and each mode uses different signal processing and damage visualization techniques. The proposed system has following advantages: (1) it provides fast inspection capabilities, (2) it also has fully non-contact or partially non-contact capabilities, and (3) it provides the ability to visualize damages that may occur in aircraft structures. The system was tested for the detection of various types artificial and real damage. The detected damage included cracks and corrosions in aluminum structures, and delamination and fatigue damage in composite structures. Debonding defects between the skin and spar in a real aircraft structure was successfully detected using this system. Experiments results showed that small damage including 5 mm cracks, 5 x 5 mm delamination, and Ø5 mm corrosion was successfully detected. These test results prove that triple functional UPI system is effective in detecting and quantifying several types of damage on various types of aircraft structures.

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REFERENCES

1. Chia, C. C., S. Y. Lee, M. Y. Harmin, Y. Choi, and J.-R. Lee, 2023, "Guided Ultrasonic Waves Propagation Imaging: a Review," *Measurement Science and Technology*, 34: 025001
2. Syed, H., and J.-R. Lee, 2018, "High-Speed Angular-Scan Pulse-Echo Ultrasonic Propagation Imager for in Situ Non-Destructive Evaluation," *Smart Structures and Systems,* 22(2): 223-230
3. Kang, S., E. B., Flynn, JY. Jeon, and G. Park, "Damage Detection on Thin-Walled Structures with Single Frequency Excitation and Wavenumber Filtering," Proceedings of the 8th European Workshop on Structural Health Monitoring, July 5-8, 2016.
4. Flynn, E. B., and G. Jarmer, "High-Speed, Non-Contact, Baseline-Free Imaging of Hidden Defects using Scanning Laser Measurements of Steady-State Ultrasonic
5. ASTM D7137, Standard Test Method for Compression Residual Strength Properties of Damaged Polymer Matrix Composite Plates.