A MOBILE ROBOTIC NON-DESTRUCTIVE INSPECTION SYSTEM BASED ON LASER ULTRASONIC PROPAGATION AND OPTICAL IMAGES

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Abstract: With the advancement of the aerospace industry, the concept of smart hangars that apply high-level smart technologies for more efficient and objective structural stability inspections has emerged. In aerospace, composite materials with excellent corrosion resistance and low weight are preferred as substitutes for metallic materials. However, because composites can have defects that are visually difficult to detect, such as interlayer separation, delamination, and voids, non-destructive testing (NDT) technology is needed to detect internal defects. Most of the existing smart hangar-related technologies rely on visual inspections, and NDT equipment relies on manual inspections. This paper introduces a mobile robotic laser ultrasonic testing system for automatic NDT of the lower surfaces of aircraft and engine cowlings. The measurement system is composed of a laser ultrasonic generation, measurement, and integrated module. Based on the robot operating system (ROS), the mobile robot can automatically move to the target point using navigation technology. By using a LiDAR camera to calculate the angle and distance of the inspection surface, the scanner's posture can be controlled to perform optimal inspections. The proposed inspection system and method are verified by inspecting CFRP specimens with artificially inserted defects and aluminum specimens with honeycomb structures.

Keywords: Non-destructive testing, Laser ultrasonic testing, Mobile robot, Smart hangar

1. INTRODUCTION

The aerospace industry uses costly, large structures and components that directly impact safety. To avoid fatal human and financial losses, it must be strictly managed. The advancement and increasing availability of the aerospace industry lead to the growing necessity and technological development of the maintenance, repair, and overhaul (MRO) industry for aircraft. Traditional MRO methods are labor-intensive and expensive, making it difficult to keep up with the increasing demand in the aerospace field. To save labor costs and inspect structural integrity more effectively and objectively, the concept of a Smart Hangar using high-level smart technology has emerged [1].

However, most of the currently developed technologies rely on visual inspection. In the aerospace industry, there is a trend to replace metal materials with composite materials that have better corrosion resistance and non-strength properties. Defects such as Barely Visible Impact Damage (BVID), which are difficult to detect visually, can occur in composite materials, such as interlayer separation, delamination, and voids. Therefore, it is of great significance to develop non-destructive evaluation techniques that are automatic, flexible, and capable of detecting internal defects.

Among the various non-destructive inspection research fields, laser ultrasonic testing that can detect defects with dense measurement intervals using lasers is widely used [2]. One of the representative methods is the Mobile Pulse-Echo Ultrasonic Imaging System. To increase the field applicability of ultrasonic inspection techniques, Space NDT Co., Ltd.'s Mobile Pulse-Echo Ultrasonic Imaging device was developed by Hong et al [3]. Wheels are attached to the bottom of the system to enhance the mobility of the inspection system, and a two-axis linear stage is used to move the ultrasonic generation and sensing devices. It uses a pulse-echo mode that has a pulse laser for the inspection body and measures the vibration with a laser Doppler vibrometer (LDV). It has the advantage of complete non-contact non-destructive evaluation. However, the LDV used to measure the ultrasonic wave must be perpendicular to the specimen for optimal inspection, which is a constraint that reduces reliability for specimens with curvature. In addition, a person must move the system every time a new area is inspected, and it is impossible to inspect areas such as the underside of an aircraft or the lower surface of an engine cowling.

The second method is the Pulse-Echo Ultrasonic Imaging System using a robotic arm [4]. A robotic pulse-echo ultrasonic imaging device has been developed by Ahmed H et al. The device uses an RGB-D camera to calculate the vertical vector through point cloud, even without a design drawing of the specimen. This overcomes the constraints of LDV and enables the application of complex structures. However, the inspection area is limited to 400 mm x 400 mm due to the range of the robot arm's payload, and it is even more limited for structures with curvature.

Therefore, this study proposes a mobile robot laser ultrasonic inspection system for automatic non-destructive inspection of the lower surface of an aircraft and engine cowling. The measurement system can be divided into a mobile robot, a laser ultrasonic generation module, a laser ultrasonic sensing module, and an integration module. The mobile robot can automatically move to the target point by implementing navigation technology based on the Robot Operating System (ROS). The proposed method allows for automatic inspection, has a wide measurement range, and is highly flexible. The remaining parts of this paper are organized as follows: Section 2 provides information on laser ultrasonic inspection technology and techniques for visualizing defects. Section 3 describes the overall system configuration and measurement principle. The experimental results using this system are explained in Section 3. Section 4 provides a brief conclusion for this paper.

2. LASER ULTRASONIC PROPAGATION TECHNOLOGY

Laser ultrasonic inspection technology

Laser ultrasonic inspection technology is a method of generating and sensing ultrasonic waves using lasers without physical contact. When a laser beam is directed onto an object, thermal elastic ultrasound is generated. The most commonly used lasers for this are Nd-YAG and CO2 lasers [2, 5], with wavelengths of 1064 nm and 1060 nm. In this study, an Nd:YAG Q-switched pulse laser with a pulse width of 6-80 ns is used for ultrasonic wave generation. The generated ultrasonic signal can be acquired using an LDV or piezoelectric (PZT) sensor. By analyzing the abnormal behavior of ultrasound, defects and damage within the structure can be detected. As it can be performed for non-contact testing at a distance, this technology is commonly used in non-destructive testing. There are various modes depending on the type of ultrasound and the location of the ultrasonic generation and sensing components. Ultrasound consists of bulk waves, which propagate in the thickness direction, and guided waves, which propagate along the surface. Using bulk waves, as the ultrasonic wave propagation path is relatively short, signal loss is low. Therefore, it is useful for thick structures. Using guided waves, testing of a wide area is possible with excitation for a relatively small area. It is useful for testing curved structures, and defects can be relatively easily identified by visualizing ultrasonic wave propagation.

The inspection modes using bulk waves are divided into pulse-echo(PE) mode and through-transmission(TT) mode, depending on the positions of the ultrasonic generating and sensing parts. The inspection modes using guided waves are divided into Q-switched Laser(QL) scan mode and LDV scan mode, depending on the usage of PZT.[6]

In PE mode, the ultrasonic generating and sensing parts are positioned on the same side of the specimen and inspect at the same point. It acquires the bulk wave that propagates in the thickness direction and is reflected from the back surface of the structure. If there is damage in the depth direction, it is reflected faster in the normal area. The depth and size of the defect can be determined by using the time difference between the normal and defect signal.

In TT mode, the ultrasonic generating and sensing parts inspect the same location from opposite directions of the specimen. As the ultrasound penetrates in the depth direction of the structure, the energy of the wave decreases if there is a defect, resulting in a difference between the normal and defect area. This mode is suitable for inspecting thick structures because the ultrasonic path is relatively short compared to other modes, resulting in less ultrasonic loss.

PZT is cost-effective and easy to install without interfering with the structure. It can be used as a transducer that converts electrical vibrations into mechanical vibrations to generate ultrasound, and also as a sensor to receive the generated ultrasound.

In QL scan mode, a Q-switched laser is used as an ultrasonic generator, and a PZT is used as an ultrasonic sensor. By visualizing the ultrasonic wave propagation, the location of defects and damage can be easily identified.

In LDV scan mode, a PZT is used as an ultrasonic generator, and LDV is used as an ultrasonic sensor. This method is used to inspect specimens in a steady state. Therefore, averaging can be performed over a short period at each measurement point for improving SNR. In this paper, QL scan, LDV scan, and PE modes are used.

<u>Visualization of the ultrasonic signal and internal defect</u>

There are technologies used to visualize ultrasonic signals and defects obtained through laser ultrasonic testing, including ultrasonic wave propagation imaging (UWPI), ultrasonic wavenumber map (UWM), and ultrasonic energy map (UEM). UWM and UEM are technologies for visualizing the results of guided ultrasonic mode testing.

The UWPI visualizes the propagation of ultrasonic waves in a three-dimensional data array by arranging one-dimensional ultrasonic signals measured at inspection points within the inspection area. The location and size of defects can be determined by scattering ultrasonic waves or phase differences [7].

The UWM emphasizes ultrasonic signals that have been altered due to defects or changes in thickness by using wavenumbers for visualization. It is suitable for defect visualization in LDV scan guided-ultrasonic propagation imaging(G-UPI), which utilizes the steady-state response at a specific frequency [8].

The UEM is a technology that finds the maximum energy of ultrasonic waves in the spatial-time domain. Since the excitation laser generates ultrasonic waves with various modes of frequencies, it is suitable for defect visualization in QL scan G-UPI that uses the laser for ultrasonic wave generation [9].

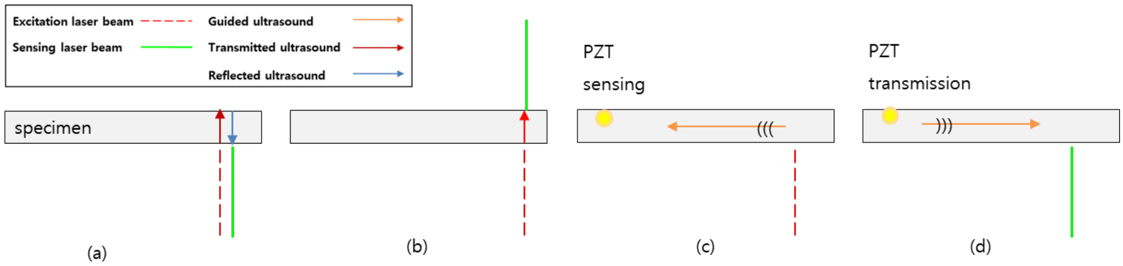

Figure 1: Schematic representation of inspection mode (a) pulse-echo mode (b) through-transmission mode (c)-(d) guided wave mode; (c) LDV scan G-UPI (d) QL scan G-UPI

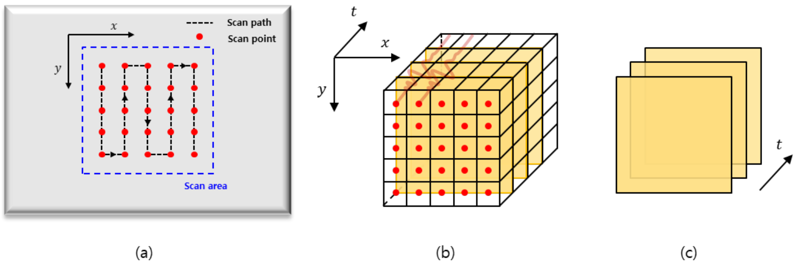

Figure 2: Schematic diagram of ultrasonic propagation imaging(UWPI) (a) laser scanning pattern (b) 3-dimensional array of measured data (c) convert image sequence to video

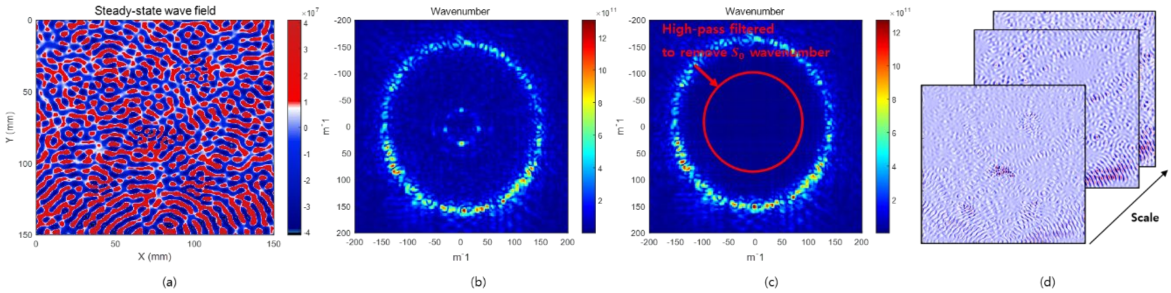

Figure 3: Process of ultrasonic wavenumber map(UWM) (a) steady-state response to the frequency of interest (b) wavenumber domain (c) high-pass filtered wavenumber domain (d) 2D continuous wavelet transform

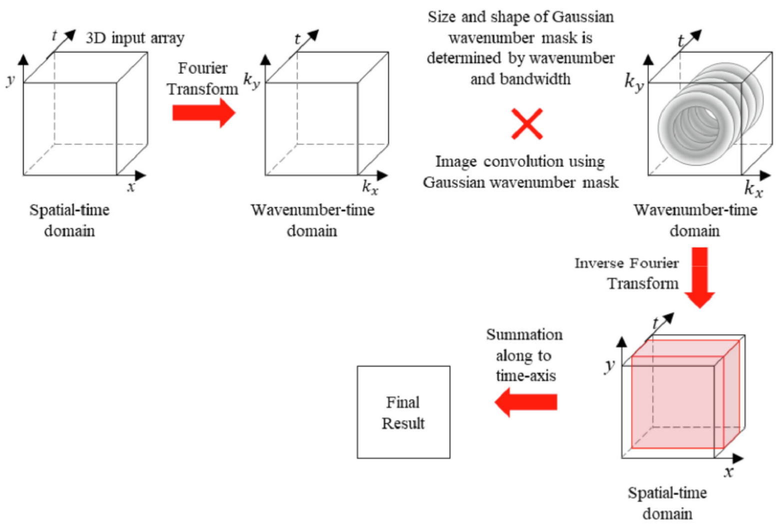

Figure 4: Process of ultrasonic energy map(UEM) [18]

3. MOBILE ROBOTIC NON-DESTRUCTIVE INSPECTION SYSTEM

The mobile robotic non-destructive inspection system consists of an ultrasonic wave propagation imaging system and a mobile robot. The ultrasonic wave propagation imaging system acquires and processes data and controls the entire system using a GUI. This system is divided into a laser ultrasonic wave generation, sensing, and integration module. Each module is used to implement QL scan G-UPI, LDV scan G-UPI, and PE-UPI. The mobile robot operates using the ROS software platform for robot application development. The equipped 2D LiDAR is used to generate a map of the inspection environment and for current position estimation and obstacle avoidance. The mobile robot automatically generates a path to the target location and moves, carrying the ultrasonic wave propagation imaging system and supplying power to it.

Laser ultrasonic generator module (QL scan G-UPI rover)

The laser ultrasonic generation module uses a Nd-YAG Q-switched pulse laser with a wavelength of 1064 nm. The laser scans the inspection area using a laser mirror scanner (LMS) system. Guided ultrasonic signals can be measured using a PZT, and the signals are acquired by a data acquisition board (DAQ). The LMS control board generates pulse trigger signals for synchronizing the entire system. It sends a trigger signal to the laser controller. Then, the laser controller generates new trigger signals and sends a signal to DAQ for saving ultrasonic signals. This trigger is used to synchronize the ultrasonic generation and acquisition processes.

Laser ultrasonic sensing module (LDV scan G-UPI rover)

The laser ultrasonic sensing module uses LDV for measuring the ultrasonic vibration of the specimen's surface. The measured ultrasonic signal is then transmitted from the LDV controller to the data acquisition board. The LMS control board generates a trigger signal that is sent to the function generator and data acquisition board. Upon receiving the trigger signal, the function generator generates a sinusoidal wave and the data acquisition board simultaneously saves the ultrasonic signal.

Laser ultrasonic integrated module (PE-UPI rover)

The laser ultrasonic integration module combines the laser ultrasonic generation and sensing module. In the QL scan G-UPI rover, the ultrasonic sensor is replaced by the LDV, while in the LDV scan G-UPI rover, the ultrasonic generator is replaced by a Q-switched laser. The stand-off distance is fixed due to the arrangement of mirrors inside the laser head. In this paper, the optimal inspection distance was set to 1.5m. To maintain a distance, the distance is measured using a LiDAR camera, and the robot's posture is controlled.

4. EXPERIMENTS AND RESULT

Three modes of laser ultrasonic inspection are implemented: QL scan G-UPI using the laser ultrasonic generation module, LDV scan G-UPI using the laser ultrasonic sensing module, and PE-UPI using the laser ultrasonic integration module.

Result of QL scan G-UPI

QL scan G-UPI rover automatically moved and avoided obstacles to the goal point shown in Figure 5, and the inspection was performed on the CFRP flat panel. The specimen had four pillows inserts and a tool drop impact. No defects were visually observed. However, using the QL scan G-UPI mode and the UEM algorithm, four pillow inserts and damage caused by the tool in the center were detected, as shown in Figure 6.

Result of LDV scan G-UPI

Similar to the QL scan G-UPI rover, the LDV scan G-UPI rover also automatically moved and avoided obstacles to the goal point shown in Figure 5, and the inspection was performed on the CFRP flat panel. By utilizing the LDV scan G-UPI rover and the UWM algorithm, the 4 pillow inserts and a tool drop impact in the center were detected as shown in Figure 7. To perform optimal inspection, the LDV beam needs to be incident perpendicular to the surface of the specimen. Therefore, after the rover reached the goal point, the normal vector of the specimen surface was calculated by using a LiDAR camera, and the orientation of the scanner was adjusted.

Result of PE-UPI

The PE-UPI rover does not require a wired connection with the PZT. So, when the user simply clicked the 'auto scan' button on the GUI, the rover automatically moved to the target point, performed an inspection on the aluminum honeycomb specimen, and then returned to the starting point after completing the inspection. The honeycomb structure was visualized using UWPI. the result is shown in Figure 8.

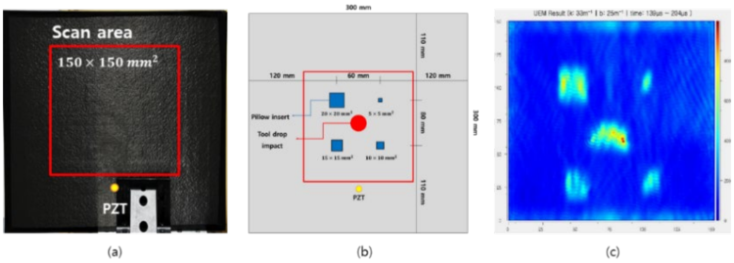

Figure 5: (a) CFRP specimen (b) pillow insert and damage map (c) UEM result of QL scan G-UPI

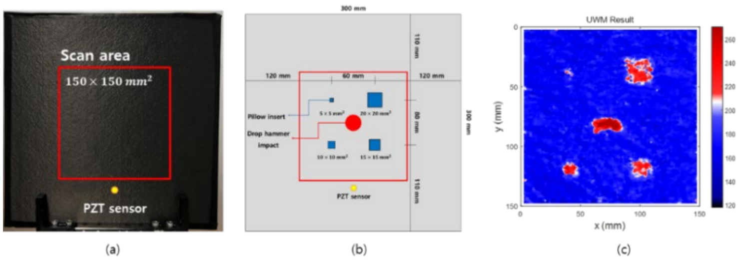

Figure 6: (a) CFRP specimen (b) pillow insert and damage map (c) UWM result of LDV scan G-UPI

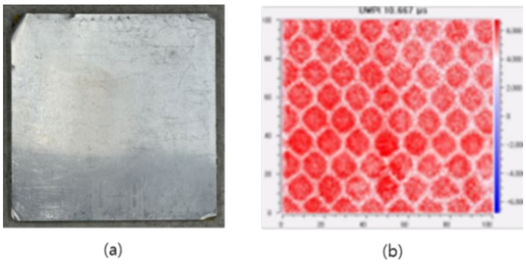

Figure 7: (a) Aluminum honeycomb specimen (b) UWPI result of PE-UPI

5. CONCLUSIONS

This paper proposes a mobile robotic laser ultrasonic testing system for automatic non-destructive inspection of the lower surface of an aircraft and engine cowling. The proposed system consists of a mobile robot and a laser ultrasonic propagation imaging system. The mobile robot enhances the system's mobility and is particularly useful for inspecting the lower surfaces of aircraft and cowling by lowering its height. The robot used SLAM and navigation based on ROS to automatically generate a path and move to the inspection point using an encoder sensor and 2D LiDAR sensor. To align the LDV beam, the normal vector of the specimen surface was calculated by using a LiDAR camera, and the orientation of the scanner was adjusted by controlling the rotation stage and the robot's posture. This method demonstrates the feasibility of inspecting inclined test objects such as the underside of an aircraft or an engine cowling. The laser ultrasonic wave propagation imaging system is divided into a laser ultrasonic generation, sensing, and integrated module to enable various ultrasonic testing modes. In the experiment results, all modes of QL scan G-UPI, LDV scan G-UPI, and PE-UPI were able to detect BVID defects or internal structures.

The system developed in this study is more flexible and costly than existing systems. Moreover, the system can be used to inspect damage-suspected areas detected by VT inspection or to inspect the lower surfaces of aircraft and cowling, among other applications.

ACKNOWLEDGMENT

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