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Multi-directional adjacent wave subtraction and shifted time point mapping algorithms and their application to defect visualization in a space tank liner

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ABSTRACT

We propose the multi-directional adjacent wave subtraction (MAWS), shifted time point (STP) mapping and variable time window amplitude (VTWA) mapping algorithms for crack visualization based on our finding that the processing direction of the adjacent wave subtraction with respect to crack orientation can dramatically affect crack visibility. The proposed MAWS, STP and VTWA mapping algorithms were implemented in a laser ultrasonic propagation imaging system and were applied in a nondestructive evaluation of an Al-alloy tank liner for space applications. A crack and void on the fusion zone of a weld were more effectively visualized using the proposed algorithms, and the crack could be visualized regardless of its orientation. The multi-directional processing results of the anomalous wave propagation imaging were visualized as video clips. The STP mapping algorithm, which maps the number of shifted time points to minimize the difference between adjacent waves, was developed to enhance the crack visualization capability of the system. Additionally, the multi-directional VTWA mapping algorithm performed data projection using the residuals of MAWS processing and provided stationary mapping results of crack-induced anomalous waves. The presented results demonstrate that the proposed visualization algorithms are promising techniques that do not overlook unknown crack orientations.

1. Introduction

A fuel tank liner, as a pressure vessel, is fabricated using metallic or plastic materials. In cases of metallic pressure vessels, welding is typically part of the fabrication process. The welding process often causes internal or invisible defects as a result of hot cracking or void creation in the fusion zone of the weld. It is hard to make diagnosis and prognosis of the origination points of hot cracking because the mechanisms for hot cracking are too complex and varied [1].

A void is a type of lack-of-fusion defects that often occur in welded joints. Voids are also serious defects, such as crack damages, especially in aerospace applications. However, they are frequently overlooked or ignored in industrial applications [2]. Tiny discontinuities could be under a state of stress concentration that leads to new crack formation. Other damages could occur on pressure vessels while in service. Due to the nature of the service of pressure vessels, they are susceptible to exposure to extremely reactive and aggressive gas and fluids that can promote stress corrosion cracks (SCCs). A SCC is a failure phenomenon that occurs in metallic materials as a result of slow, environmentally induced crack propagation [3]. External and open cracks and voids could be detected through visual testing, but damages and defects beyond visual testing are tested through various nondestructive testing methods, including magnetic field testing, penetration testing, eddy current testing, and ultrasonic testing. Jha et al. investigated SCCs on the propellant tank of a satellite launch vehicle [4] and found SCCs along a weld bead boundary through macroscopic observations. In other studies, a surface crack in the fusion zone of a weld has been detected via thermography [5]; void inspection has also been implemented through macroscopic observations and through ultrasonic [2] and radiography techniques [6].

Most non-destructive testing, including visual testing and the ultrasonic technique, requires high accessibility to humans, and the inspection results of some techniques that are designed to use a contact probe (or touch-triggering-probe) are dependent on the shape of the target. In visual testing, it is not possible to investigate damages and defects using the naked eye if they exist inside of the target structure. Radiography generally requires a special space for inspection and has low detectability such that the shape of the target or position of the X-ray tube may negatively affect the results. Conventional ultrasonic testing systems are configured with contact pulse-echo ultrasonic transducers. Thus, the surface shape of a target could affect ultrasonic techniques; such techniques also require highly trained users who are able to analyze ultrasonic signals and images.

In this paper, we propose the multi-directional adjacent wave

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subtraction (MAWS) algorithm for crack visualization, which is based on our finding that the processing direction of the adjacent wave subtraction (AWS) can highly affect crack visibility as a result of crack orientation. The proposed MAWS is implemented in a laser ultrasonic propagation imaging (UPI) system [7]. A reciprocal setup using the scanning source and fixed sensors presents the wave propagation pattern that emerges from the sensor locations. The visualized wave propagation pattern includes incident wavefields, showing anomalous wavefields, such as the diffracting waves, reflecting waves, scattering waves, and confining waves that result from material discontinuities, e.g., a weld, hole, crack, bolt, stiffener, debonding, delamination, corrosion, erosion, dissimilar material boundary, etc. While MAWS is processing, the numbers of shifted time points (STP) of one of two adjacent waves are displayed, using a color intensity map, as a 2D image. The new damage and defect visualization algorithms are applied toward nondestructive evaluation (NDE) of an Al-alloy tank liner for aerospace applications. NDE experiments for cracks and a void are performed on the Al-alloy tank liner to validate the applicability of the algorithms for in-process quality control during the manufacturing and testing of complex pressure vessels.

2. Proposed defect visualization algorithm

2.1. Review of ultrasonic wave propagation imaging

To visualize ultrasonic wave propagation, finite element (FE) simulations are widely used; the simulation results are validated by analyzing the 1D time domain signals acquired through real tests [8]. This type of simulation requires considerable calculation time but has low accuracy even when used for simple structures. On the other hand, the UPI system has provided real-time videos for wave propagation in real-world structures. The UPI system scans an area with a constant laser impingement interval (Δ), as shown in Fig. 1(a). All the grid points in a $L_H \times L_V$ scan area (where L_H=width of the scan area, L_V=height of the scan area) are stimulated by laser pulses that are steered by a laser mirror scanner (LMS) placed between the target and the laser. The impinging laser pulse generates a thermal elastic wave, and the ultrasonic wave signals generated at all grid points are acquired by a contact, noncontact, or wireless ultrasonic sensor or multiple use of the sensor. The acquired signals are then processed by using various imaging algorithms for damage and defect visualization, which are a part of the UPI system. The basic algorithm is an ultrasonic wave propagation imaging (UWPI) algorithm [7], which performs three-dimensional data rearrangement shown in Fig. 1(b). The UWPI algorithm, that is based on raw ultrasonic signals, which produces a video clip that shows how the ultrasonic wavefield propagates over the structure.

2.2. Multi-directional adjacent wave subtraction algorithm and shifted time points mapping algorithm

Anomalous wave propagation imaging with an AWS algorithm was introduced in Ref. [9] to enhance the visibility of anomalous waves by removing incident wave components and amplifying anomalous wave components from raw signals. The AWS method is based on the fact that adjacent waves in the scanning grid are almost the same, and their subtraction effectively enhances the visibility of anomalous waves while highly suppressing incident waves. The algorithm requires a signal matching process with wave shifting before the subtraction step.

In Ref. [9], omnidirectional damage (delamination of composite structures) generated confining waves within the new damage-induced boundary; this was successfully highlighted by the conventional AWS algorithm. In the case of damage with a specific orientation, however, we found that the conventional AWS, without considerations regarding the damage orientation and the processing direction of the AWS, fails to visualize crack-induced scattering depending on the crack orientation because the crack-induced scattering waves also show directivity in propagation. In other words, the AWS, using horizontally adjacent waves, cannot effectively visualize a horizontal crack because both horizontal waves show a high similarity in the scattering wave and in the incident wave. In this paper, first, anomalous wave propagation imaging with a multi-directional adjacent wave subtraction (MAWS) algorithm is proposed to prevent failure in crack detection because of crack orientation, which is unknown before inspection.

Fig. 2(a) shows a flow chart of the MAWS algorithm. For a scan area with a width and height of L_H and L_V, respectively, the number of grid points on each axis could be expressed as follows:

$$i_m = \frac{L_V}{\Delta}+1, \quad j_m = \frac{L_H}{\Delta}+1 \tag{1}$$

where Δ is the scanning interval. Every point in a scanned area, except the points on edges and corners, has eight adjacent signals. For the first signal $S_{i,j}$, as shown in Fig. 2(b), the three adjacent signals placed in the 0, 45 and 90 degree directions ($S_{i,j+1}$, $S_{i+1,j+1}$ and $S_{i+1,j}$) are used for the MAWS processing. In the proposed MAWS algorithm, one of two adjacent signals is shifted in the time domain. The MAWS algorithm tries to determine the optimal amount of time point shifting in the sampling rate to obtain the highest similarity between the first and second signals. The time shifted one of the second signal is expressed as $S^*_{i,j+1}$, $S^*_{i+1,j+1}$ or $S^*_{i+1,j}$ depending on the processing direction. The

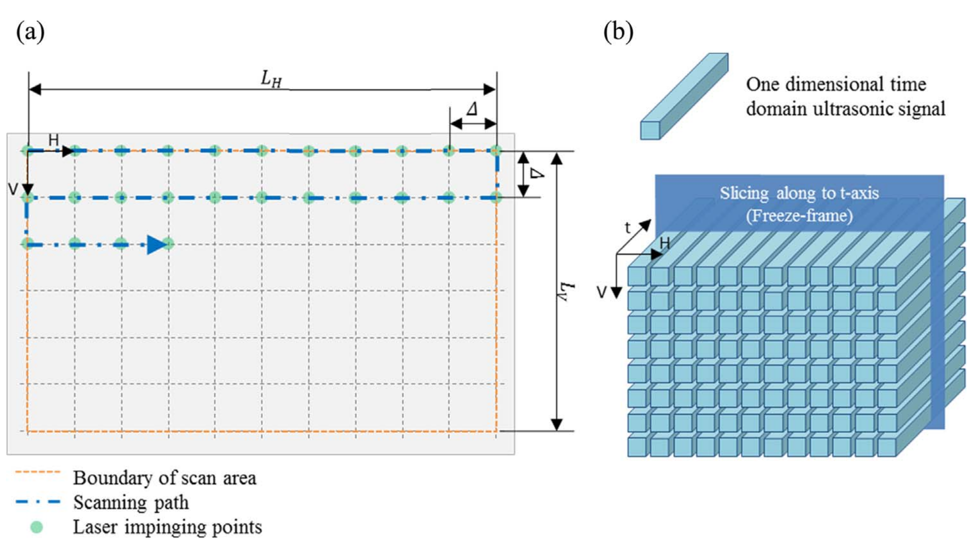

Fig. 1. Schematic diagrams of (a) laser scanning technique, (b) Data rearrangement for UWPI video clip generation.

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