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3D RECONSTRUCTION OF BARELY VISIBLE IMPACT DAMAGES SHAPE FROM LOCAL COHERENCE DIFFERENCE BETWEEN LASER ULTRASOUND SIGNALS

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ABSTRACT

Carbon-fiber reinforced plastics (CFRP) are widely used for aircraft structure manufacturing due to their efficient stiffness to mass ratio. Numerous failure modes can occur in these materials; therefore, inspections are required both in production and in the field. The increased use of CRFPs has also raised requirements for fast and reliable NDT techniques capable of inspecting large components within a short time.

Recent developments in the field of laser-ultrasound (LU) lead to fast all-optical systems providing detailed images with sub-ply resolution. However, manual analysis of such images can be time-consuming and infeasible in the case of large components inspection. Therefore, automatic signal processing methods of these scans are required. The main challenge in the implementation of such methods is multi-modal nature of laser ultrasound generation. Surface and shear waves create artifacts in B-scans and can hinder defects detection through simple signal gating.

In this paper, we present a short-time correlation techniqe that analyzes similarities between a reference obtained for a pristine structure and the inspected signal. Any differences between the signals are observed as a drop in local correlation coefficient which can be acquired and presented in the form of a time-of-flight C-scan.

Keywords: impact damage, CFRP, BVID, Laser ultrasound,

NOMENCLATURE

CFRP	Carbon fiber reinforced polymers
LU	Laser-Ultrasound
SNR	Signal to noise ratio

1. INTRODUCTION

Carbon fiber reinforced polymers (CFRP) are increasingly used for manufacturing of lightweight aircraft structures. Because of numerous advantages, including high strength, stiffness, and low thermal expansion, composite materials account for as much as 50% of the structural mass of the modern aircraft [1]. On the other hand, composites are susceptible to internal damages that can arise during manufacturing or exploitation. Low energy impacts, which would create only small dents in metallic sheets, generate defects that are barely visible at the surface of the CFRP structures but result in large delaminations in deeper layers. Therefore, the early detection and imagining of these defects is essential for the safety of the CFRP structures.

To deal with these problems, a number of non-destructive testing (NDT) techniques were developed. Single-sided access is required to perform *in situ,* evaluation, therefore, transient thermography [2] or shearography [3] is used for preliminary screening and contact ultrasonic (US) techniques are used for more profound imaging of the defects [4]. Multi-element array transducers are commonly used to speed-up data acquisition. To facilitate the processing of these large sets of data, advanced image processing algorithms are under constant developed [5].

Recently, an all-optical laser ultrasonic (LU) system operating at a kHz pulse repetition rate was reported [6]. LU has many advantages in comparison with the conventional US. First of all, LU is a non-contact method, that does not use coupling agents. Second of all, a laser-transient US is ultra wide-band, which results in at least three times higher spatial resolution than the conventional US transducers with the same characteristic frequency. It was reported that LU can produce high-resolution images of quality comparable to the computed X-ray CT without the need for sample extraction [7].

The high-resolution 3D scans provide detailed information on the inspected object. Computed assisted processing algorithms could highly reduce the time required for interpretation. The main challenge in the implementation of the most straight-forward methods based on signal gating is that the laser excitation operating in the thermo-elastic regime can produce different elastic modes simultaneously. Shear and surface waves superimposed with longitudinal waves create image artifacts hindering signal gating and damage detection in B-scans.

In this paper, we present a signal processing technique that can extract damage related information from the 3D sets of LU data without removing surface wave signals. The method is based on short-time correlation between a baseline reference created from signals averaged over an undamaged sample area and signals obtained from the inspection. Echoes reflected from the defects change the local shape of the waveform which will be detected as a drop in local-time correlation.

2. MATERIALS AND METHODS

2.1 Multimodal LU generation

The characteristics of the laser generated ultrasound depend on the light interaction with the inspected surface. Here, we assume that the epoxy is semi-transparent at the wavelength of the pump laser, and therefore, most of the laser pulse is absorbed by the carbon fibers. This assumption is valid for lasers operating at 1000 nm wavelength range, e.g. Nd:YAG and diode-pumped fiber lasers. The thermal expansion of the fibers generates omnidirectional ultrasonic waves. The longitudinal waves travelling along the direction normal to the surface of the sample are used to image the interior of the sample. The resulting US signal can be modelled as a single bi-polar waveform that can be approximated as a derivative of the Gaussian waveform as

$$p_0(t) = -t/\sigma^2 \exp(-(t-t_0)^2/2\sigma^2), \qquad (1)$$

where t_0 is a time instant when the excitation occurs and 2σ is the delay between both interfering pulses. The vibration velocity obtained at the surface can be approximated as a convolution of this pulse with a scaled delta function describing depth and reflection coefficient of consecutive layers or defects.

It appears, however, that the laser excitation operating in the thermo-elastic regime can produce different elastic modes simultaneously. Surface waves generated within the laser spot can be sensed by the detector and are visible in the resulting B mode images.

2.2 Short Time cross-correlation

A standard procedure used in ultrasonic testing is to set gates to watch the A scan amplitude within the region of interest. The gate level is selected to detect defect-related impulses exceeding a given threshold. Also, time duration of the gate has to be adjusted accordingly to avoid false alarms resulting from the dead zone or back-wall impulses. In the case of LU, the significant amplitude of the surface wave can exceed the assumed gate level and be erroneously taken as an echo of the defect.

To overcome this problem, we present local-time coherence difference approach [8] investigating signal similarities within a short-time window. The method is based on an assumption that a wave reflection from a defect, interfering with the signal of a healthy structure, change the waveform shape. To reveal these changes, the normalized correlation coefficient can be calculated in a short-time window as

$$\bar{\bar{R}}_i\,(t_c) = \frac{\int v_i(t) \cdot r(t) \cdot w(t-t_c)dt}{\sqrt{\int v_i^2(t) \cdot w(t-t_c)dt \cdot \int r^2(t) \cdot w(t-t_c)dt}} \qquad (2)$$

where v_i is i^{th} A-scan, r is signal without defects, $w(t-t_c)$ is temporal window for windowed comparsion, t_c is the center of the window.

The reference waveform for the algorithm is obtained by averaging A-scans over an undamaged area or could be obtained from a calibration block manufactured from exactly the same material as the inspected object.

2.3 Experimental setup

The experiments were carried out using a LU system described in detail in [6]. A diode-pumped nanosecond laser was used to excite the surface of the sample in a thermoelasticregime. The non-contact detection was performed by fiber-optic Sagnac interferometer and the signal was sampled at 200 MHz rate using analog to digital converter. A CFRP sample with the impact damage induced by 25J strike was fixed to the XY linear translation stage. The sample was scanned with a step of 0.05 mm for both axes. Position synchronized output was used to trigger the pump laser. The laser allows over 1000 firings per second, but due to the time of cooling while changing excitation spot, it avoids overheating of the sample by the pump laser. The probe-laser beam was oriented normal to the surface of the sample. In order to excite and measure the response of the structure in the same spot, the pump-laser pulses were delivered at 40 degrees inclination from the normal.

3. RESULTS AND DISCUSSION

Using the LU system a complete set of 3D data was acquired. An example of a raw B-scan was presented in Fig. 1a. Initial pulse, back-wall echo, and damage-reflected wave components can be clearly seen in the figure. The surface wave can be observed as a dark area reaching 1.5 mm.

In the first step, a reference was created by averaging 50 A-scans over the undamaged area. Next, the short-time correlation coefficient between the reference and subsequent A-scans was calculated. An example of correlation coefficient distribution was presented in Fig 1 b. By comparing the raw B-scan and the correlation coefficient distribution presented in Fig. 1a and b respectively it can be seen that defects existing in the structure lead to a drop of the correlation coefficient. The remaining part of the image has a relatively high correlation coefficient. It can be observed, however, that the correlation coefficient drops with the depth, which is not surprising since US attenuation reduces signal amplitude which decreases the signal to noise ratio.

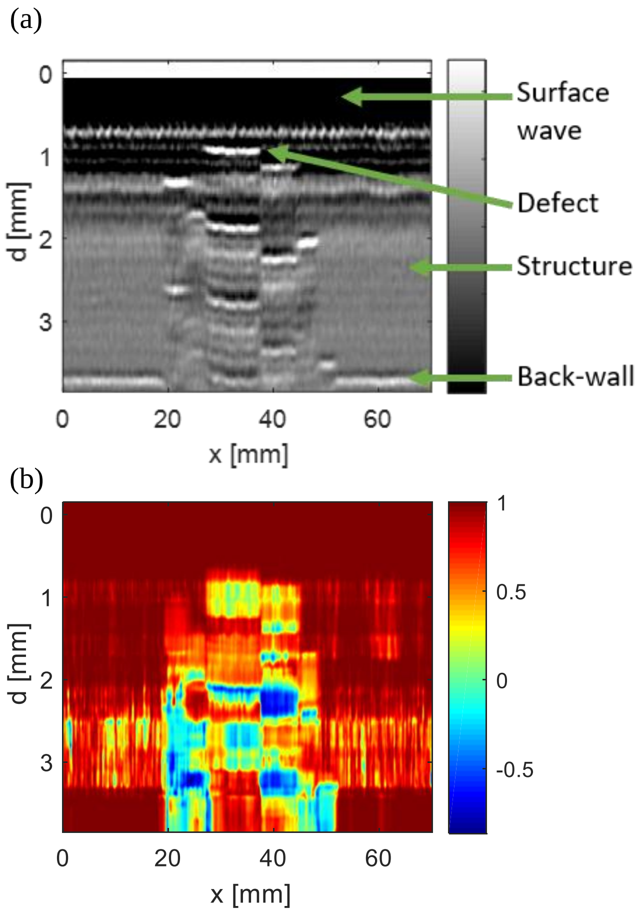

FIGURE 1: B-SCAN OF RAW DATA a) SHORT TIME CROSS-CORRELATION COEFFICIENTS FOR $\tau = 0$ BETWEEN REFERENCE AND WINDOWED SIGNAL b)

The complete dataset was processed using the local-time coherence algorithm. A 2D Gaussian smoothing window of 25x25 points was applied to the dataset. Next, the time of flight at which the correlation coefficient dropped below the arbitrary assumed value of 0.1 was found and presented in the form of time-of-flight C-scan (Fig 2). A typical shape of defects increasing with depth can be seen in the image.

4. CONCLUSION

The presented normalized short time cross-correlation method was demonstrated as an effective tool for impact damage detection and visualization. As expected, the delamination size was found to be increasing at subsequent deeper layers. The results can be used to estimate 3D shape of the defect, noting that no US energy can travel through delamination and the shape estimation can be based on first delamination reflection only.

Since the method investigates coherence between the signals, the sufficient SNR is needed. Because of the US attenuation using this method at greater depths can be challenging or even impossible. On the other hand, surface wave artifact is problematic only in the initial part of the signal, therefore, a hybrid method based on gated waveforms can be possibly applied.

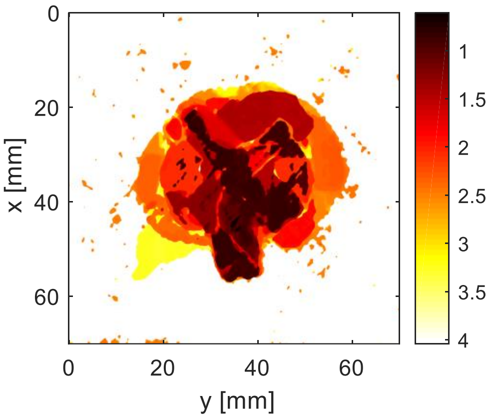

FIGURE 2: C SCAN IMAGE ILLUSTRATING THE DEPTH OF THE DEFECT

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