PERFORMANCE OF ULTRASONIC IMAGING WITH FREQUENCY-DOMAIN SAFT

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1. INTRODUCTION

Ultrasonic testing is widely used for detecting, locating and sizing flaws in many applications. Lateral resolution and signal-to-noise ratio (SNR) can be improved by focusing the acoustic field with lenses or curved transducers or by using a computational technique that performs the focusing numerically. The last method is known as the Synthetic Aperture Focusing Technique [1]. Originally developed in the time domain, SAFT can be advantageously implemented in the frequency domain (F-SAFT). F-SAFT is based on the plane wave decomposition of the measured ultrasonic field [2] and provides an accurate and time-efficient algorithm for 3-D reconstruction. Also, laser-ultrasonics has brought practical solutions to a variety of NDT problems that cannot be solved by using conventional ultrasonic techniques [3, 4]. It uses two lasers, one with a short pulse for the generation of ultrasound and another one, long pulse or continuous, coupled to an optical interferometer for detection. Recently, we have introduced several improvements to the F-SAFT algorithm and we have coupled it to laser-ultrasonics [5, 6]. In this paper, we demonstrate the capability of this technique for detecting and characterizing flaws in structural materials.

2. F-SAFT METHOD

We consider that the generation and detection beams are focused at the same location onto the surface. Following acquisition of a grid of signals over the surface of the tested part, traditional SAFT identifies a defect by summing all the signals within a certain area (the aperture) after giving proper time-delays. This data processing approach, while straightforward in its principle and implementation, is very computation intensive. An alternative method is F-SAFT whereby the data processing is performed in the 3-D Fourier space using the angular spectrum method [2]. Starting from the measured ultrasonic field at the sample surface, a 3-D Fourier transformation is performed. Then, the transformed field is backpropagated to any depth and an inverse 2-D Fourier transformation yields the sub-surface image.

Recent improvements to the F-SAFT algorithm include temporal deconvolution to enhance both axial and lateral resolutions, control of the aperture to improve signal-to-noise ratio, as well as spatial interpolation in each sub-surface plane. The control of the aperture also allows reduction in the sampling requirements therefore making the technique more attractive for industrial use. Usually, the amplitude of laser-generated longitudinal (L) waves decreases away from the normal to the surface and one should limit the aperture to a maximum value to avoid the addition of noise. Also, laser-generated shear (S) waves have an angled emission pattern and one should use an annular aperture for the same reason. Introducing a lower limit could also be useful for L-waves to reduce direct contribution from the backwall and improve contrast in the image. By considering the direction cosines of the wave components, it follows a condition on the temporal frequencies to be included in the summations [6]. For L-waves, it has been shown that the SNR rapidly increases with aperture angle, reaches a maximum for about 30^o and then progressively decreases by at least 6 dB, as a result of including components that contributes more to noise than to coherent signal. In addition, the processing time is further reduced since less data points are included in the summations. Other improvements in the implementation of F-SAFT can be found in Ref. [5].

3. RESULTS AND DISCUSSION

A first application to illustrate the capability of F-SAFT with laser-ultrasonics is the detection of inclusions in steel slabs. The presence of small defects in cast slabs (voids and particular inclusions), mainly found within a depth of about 10 mm below the surface, is hard to avoid and could lead to a variety of problems down the processing line. Samples taken from an industrial steel slab and having flat-bottom holes at different depths were tested. The inspection was performed in a scanned area of 28 X 28 mm^2 with a step size of 0.2 mm. The F-SAFT reconstruction was made with L-waves and results on a descaled sample are presented in Fig. 1. The figure includes the amplitude C-scans (top) gated at the depth of the holes, and B-scans (bottom) across the holes. In Fig. 1a, the presence of the deepest 1 mm hole is seen in the C-scan (at the intersection of the two cursors), with a depth estimated from the B-scan to be 3.6 mm. The B-scan also shows the 2 mm hole at a slightly different depth. In Fig. 1b, the C-scan shows the presence of the 1 mm hole near the surface and the depth estimated is about 0.9 mm by considering the strongest reflections in the B-scan. It is found that a step size of nearly 1 mm would be sufficient to detect the 1 mm holes. A statistical approach where randomly selected areas on the steel slab are inspected can be considered in practice.

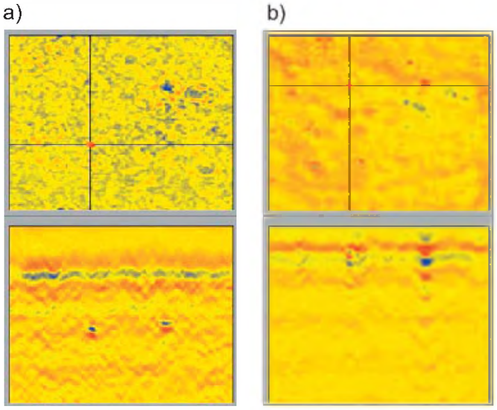

Fig. 1. C-scan (top) and B-scan (bottom) of a descaled sample, with the 1 mm holes at a depth of 3.6 mm in a), and near the surface at 0.9 mm in b).

A second application is the visualization of stress corrosion cracks (SCCs) using laser-ultrasonics. Tested samples were made from stainless steel and contained a few SCCs, each typically less than 0.05 mm wide and from 0.5 to 5 mm deep. The samples were interrogated from a surface opposite to cracking. The step size of the scan was 0.2 mm and the scanned area was about 40 x 40 mm^2. The aperture was from 5^o to 25^o for L-wave reconstruction and from 35^o to 55^o for S-wave reconstruction. C-scans obtained using L-waves and S-waves are compared to the images by liquid penetrant testing (PT) in Fig. 2. Each C-scan was obtained by selecting the maximum amplitude in a narrow gate at depths corresponding to the cracking surface. F-SAFT provides very fine images of the surface which contains SCCs with a detectability that can exceed that of PT, being the most sensitive method to visualize fine cracks. When comparing images, the spatial resolution of F-SAFT with S-waves is higher. Indeed, B-scan images reconstructed with L-waves show the crack roots as a lack of signal having a width not well defined. The image with S-waves shows a feature having a cross-like shape ("X" shape), the center of which has the maximum amplitude and is located at the position of the crack root on the surface. The "X" shape is related to the existence of a corner near the crack root and further investigations have shown that the amplitude at the cross point is indicative of the crack depth. Notice that the presence of the "X" shape is a particular feature that only laser-generated S-waves can produce.

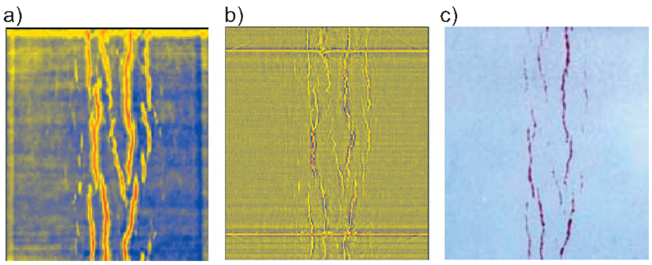

Fig. 2. C-scans of the cracking surface on a SCCs sample using a) L-waves, b) S-waves and c) PT.

A third application is visualization of delaminations along curved interfaces. An example is Mg/Al casting, composed of an Al core enclosed in a Mg shell and investigated by an automotive manufacturer for engine parts. In the case of a Mg/Al interface not parallel to the top Mg surface, the ultrasonic wave can be reflected obliquely from the interface to any location on the Mg surface. F-SAFT allows synchronization of the ultrasonic signals scattered back in the different directions. A testpiece of Mg/Al casting was made with flat-bottom holes drilled in the Al part down to the interface of the two alloys. The inspection was from the Mg surface in an area of 40 x 15 mm^2 with a step size of 0.2 mm. Fig. 3a and Fig. 3b are C-scans taken at depths of 8.2 and 9.7 mm respectively. Fig. 3c is a B-scan showing the curved Mg/Al interface as well as the depth of the two C-scans. In Fig. 3b, two flat-bottom holes of diameters 10 and 5 mm are observed at a depth of 9.7 mm where the interface is almost flat and parallel to the scanned surface. In Fig 3a, corresponding to a depth of 8.2 mm, a horizontal line of variable amplitude is observed. This line is the intersection of the curved Mg/Al interface with the observation plane and the darker amplitudes are indicative of delaminations.

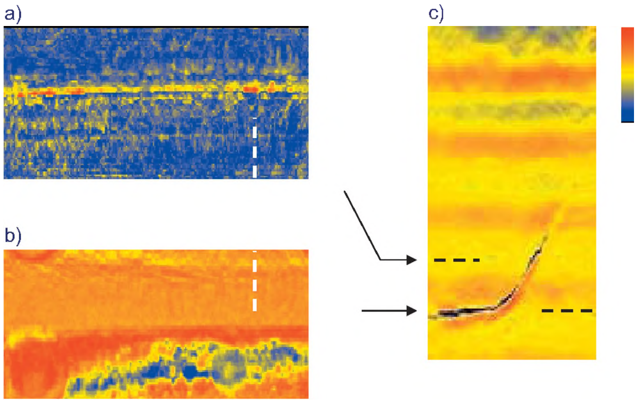

Fig. 3. SAFT images of a non-parallel Mg/Al interface. The C-scans a) and b) have depths indicated in the B-scan c). The B-scan is at position indicated in a) and b).

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