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Nondestructive evaluation of composite and porous materials by 3D acoustical imaging

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In this work, based on the use of high frequency (20MHz) focus ultrasonic transducer and echography, a high-resolution three-dimensional acoustical imaging technique has been developed, permitting 3D reconstruction of the internal structure of materials at mesoscopic level. The data acquisition is realized by the combination of A, B and C scan in reflection mode. The 3D material structure is obtained by applying a surface reconstruction algorithm to the scanned volumetric data. Two application examples are shown to valid the method: the imaging of a 2D textile composite sample before and after a mechanical impact testing, and a porous bone sample. The material structure can be quantitatively evaluated and analyzed.

1 Introduction

The mesoscopic architecture of structural materials like textile composites (two or three-dimensional braided fiber structure in polymer matrix) and porous materials (random pore structure) determines the macroscopic performances and properties of the materials. Its evaluation and characterization is a major issue in the process, mechanical testing and in-situ safe use of such materials. At macroscopic level, the materials can be quantitatively evaluated by measuring their equivalent physical parameters such as mechanical modulus, elastic constants, anisotropy, porosity, etc, which represent the averaged global or final performances of the materials. However, these properties are based on the micro- and mesoscopic structure forming or constituting the materials. Therefore, nondestructive inspection and evaluation at mesoscopic level have much more significance and importance in material process, characterization and fabrication. Imaging technique is the most effective means for reliable examination of the internal structure of the materials, and defects evaluation and analysis.

There are two imaging techniques capable of “seeing” into internal structure of opaque materials, i.e. X-ray micro computed tomography (μ CT) [1,2] and ultrasonic echography [3,4]. The μ CT, in which the image contrast is based on the material absorption, provides 3D imaging in a very high spatial resolution (several μ m), but has disadvantages of using heavy and non-portable equipment and need of human operator protection. The 3D imaging is time-consuming (hours) either in data scanning or in image reconstruction. By contrast, the acoustical imaging has simplicity, rapidity and low cost. The imaging contrast is related to the mechanical properties (acoustic impedance) of materials. However, its imaging mechanism and image reconstruction are much complicated due to the complexity of acoustic wave reflection-transmission in complex media. The resolution of the acoustical imaging, depending on the wavelength hence the wave frequency used, will be limited due to the high wave attenuation at high frequency.

The present work uses acoustic microscopy at relatively low frequency (20MHz) to realize 3D ultrasonic imaging and analyze mesoscopic structure of a 2D textile composite and a porous material (cortical bone). A novel and robust algorithm to reconstruct the material internal structure by 3D surface objects from volumetric data of wave reflection was developed and implemented. It allows 3D visualization of lamination and textile structure and eventual defects like impact crack, delamination in a textile composite, and pore structure in a porous bone.

2 Methodology

2.1 Acoustical imaging system and volumetric dataset acquisition

The 3D imaging system is an acoustical microscope [5] equipped with a focusing transducer operating at 20MHz center frequency (0.25-inch aperture and 0.75-inch focal length). Working in immersion and reflection mode, the transducer is excited by a wideband pulse generator (Olympus 5900PR transmitter-receiver). The signal acquisition is realized using a digital oscilloscope (HP 54600A), and the mechanical scanning is carried out with a 3-axis (x-y-z) stepper motors system, both controlled by a PC, as shown in Figure 1-(a).

3D-image data of a material sample is obtained by 2D scanning in x-y plane with an adjustable step resolution (typically 20-100 μ m) while registering A-mode echography $s(t)$ at an adjustable sampling rate (typically 100MHz) in repeat mode (averaged in 8 acquisitions) for noise reduction.

A GUI (Graphical User Interface) programming in matlab was developed to synchronize and execute the scanning and data acquisition, and visualize the A, B, C scan images in real time. An example of the volumetric dataset $V(x,y,t)$ displaying is represented in Figure 1-(b).

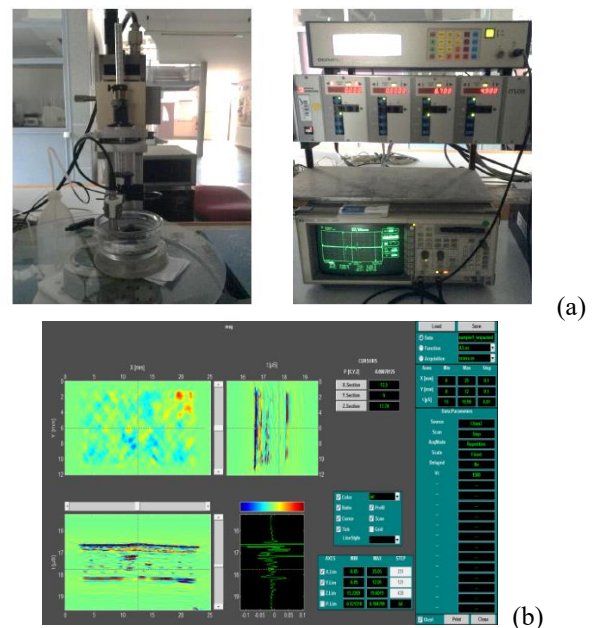


Figure 1 – Acoustical imaging system (a) Equipment and setup (b) Volumetric dataset acquisition software.

2.2 Algorithm for 3D surface objects reconstruction from volumetric data

To analyze the mesoscopic structure of complex materials, there is needs to develop efficient algorithm to represent the structure in a 3-dimensional way, usually by the surface objects (interface contours). For acoustical imaging, the image data nature is very different from that of the X-ray tomography that is based on “iso-surfaces” extraction [6]. The acoustical data representing an interface reflection is a time pulse signal with a certain width and peak amplitude [7,8]. Therefore, the reconstruction of interface contours is to determine the time when pulse amplitude attains its maximum and localize where it happens. A robust algorithm was developed to perform the interface contours extraction from acoustic volumetric data and is describe as following.

The volumetric data $V(x, y, t)$ is considered as a set of C-scan slices at fixed time t_i for $i = \{1, 2, \dots, i_{max}\}$. Taking the example as shown in Figure 2, the algorithm flow is

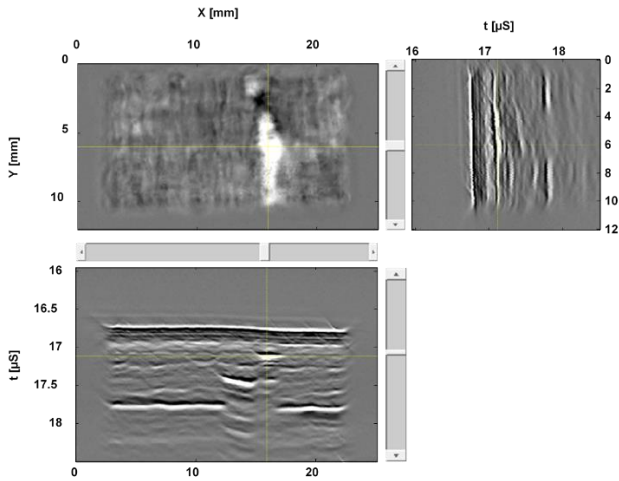


Figure 2 - Acoustic volumetric data obtained for a 2D textile composite sample (20x10mm² in size and 2 mm in thickness)

set a threshold $h(t_i)$, variable as a function of t_i , corresponding to “Time Gain Control” (TGC) for compensation of wave attenuation as the propagation depth (or t_i) increases in the material;

for slice_number $i = 2$ to $i_{max} - 1$

find all pixels (x_i, y_i) in the slice i $V_i(x, y, t_i)$ where peak amplitude occurs (tops of reflection pulses) with the peak value superior to the threshold $V_i > h(t_i)$, they are determined by the maximum value of three successive time points in slices $i-1, i, i+1$ having the same pixel location (x_i, y_i) ;

%% Figure 3-(a)

do assembling and labeling these pixels according to their connectivity, obtaining labeled surface components $S_L = t_{nL}(x_{nL}, y_{nL})$

%% Figure 3-(b)

if the surfaces found in slice i have connectivity with those obtained in step $i-1$:

do fusion (or expanding) these surfaces and re-labeling them;

display labeled surface objects S_L in 3-dimensions with their location $\{x_{nL}, y_{nL}, t_{nL}\}$, the surface pixels is lighted in grey level or pseudo-colored using their peak amplitude value $V_n\{x_n, y_n, t_n\}$ representing the reflection intensity. The surfaces objects can be selected, zoomed and observed at a desired space-orientation angle.

%% Figure 3-(c)

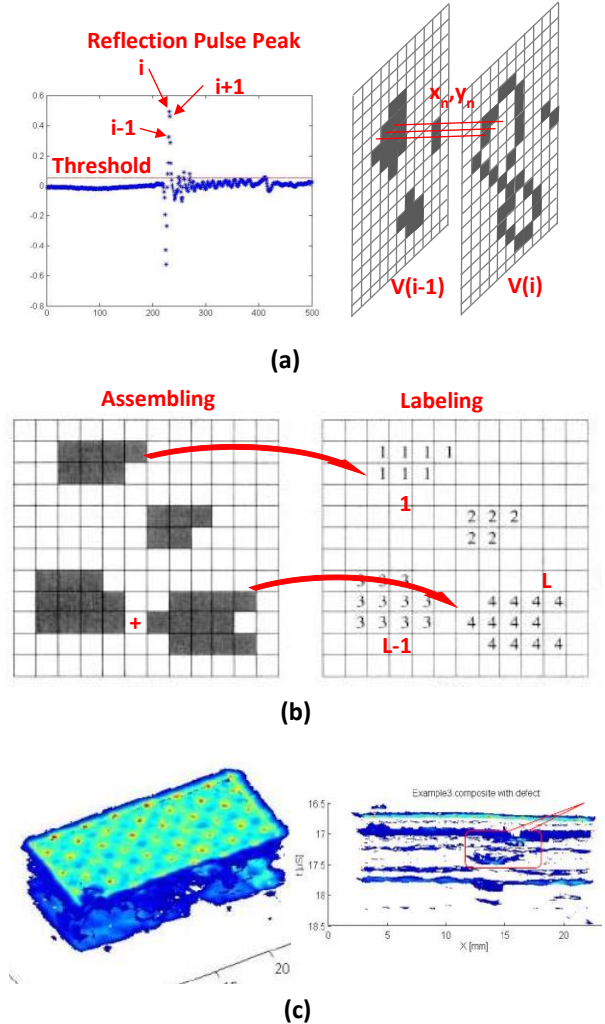


Figure 3 - Surface objects (reflection interface contours) extraction from acoustic volumetric dataset, (a) Threshold setting and pulse peak (top value) finding; (b) Surface objects formation and labeling; (c) Surface objects localization, displaying and observation.

3 3D structure imaging of 2D textile composite and porous material

The surfaces reconstruction of the above example were obtained for a textile composite sample of architecture $[(0^\circ/90^\circ)^{12K}, (+45^\circ, -45^\circ)^{NCF}, (-45^\circ, +45^\circ)^{NCF}, (0^\circ/90^\circ)^{3K}]$, constituting of 4 different layers, each with two sublayers. The imaging was realized after an impact test of the sample. Both sublayer structure and impact delamination/rupture defects can be very well observed in details, in particular the defects size and localization. To show the woven fabric structure, Figure 3 gives the C-scan images obtained at

different depths of the sample before its impact test. The sublayer structure of the composite can be analyzed. The application of a 2D-FFT at these images can determine the space period and orientation of warp and weft (Figure 4-(b), (d)), and the average fiber spatial alignment density (Figure 4-(c))

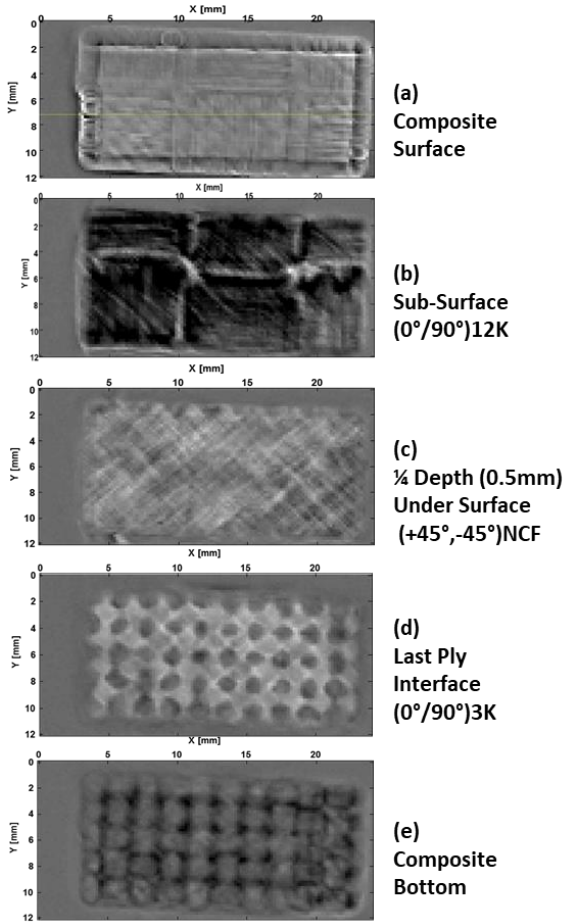


Figure 4 – Mesoscopic woven fabric structure of a 2D textile composite $[(0^\circ/90^\circ)^{12K}, (+45^\circ,-45^\circ)^{NCF}, (-45^\circ,+45^\circ)^{NCF}, (0^\circ/90^\circ)^{3K}]$.

In the case where the sample surfaces and interfaces are not plane or horizontally placed in the scan plane, or in the case with complex defect geometry, it will be difficult or impossible to observe well the material structure in a C-scan plane. Therefore, the surface objects reconstruction in 3-dimensions will become important. Figure 5 represents the imaging and reconstruction for a composite plate sample having the same structure as the above one. The two results were obtained by scanning on each of the two sides of the sample.

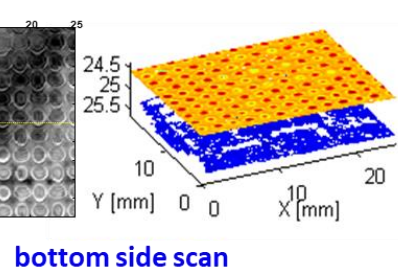
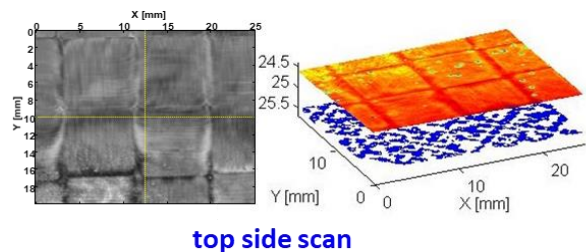


Figure 5 – Imaging and structure reconstruction of a composite plate by scanning each of the two side of the sample.

At last, Figure 6 gives the acoustical imaging of a porous material (cortical bone sample) to show and analyze its pore structure. The result is compared to that obtained by using micro X-ray tomography. It is hoped that the acoustical imaging can be used to perform real-time (or quasi real-time) imaging during tensile test in the purpose to evaluate the mechanical strength of the sample.

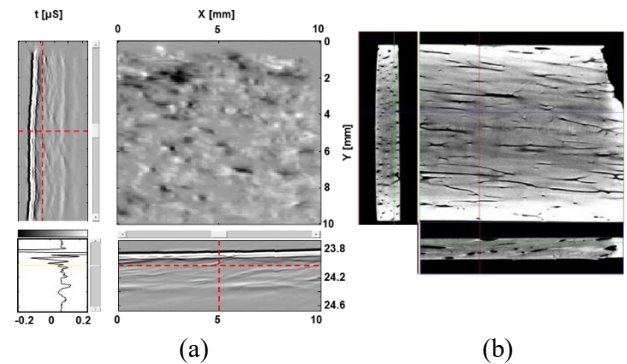


Figure 6 – Imaging of porous material (cortical bone) (a) 3D echography (b) X-ray tomography

4 Conclusion

A 3D acoustical imaging technique was developed to visualize the internal structure and defects of complex materials at the mesoscopic level. Compared to μ X-ray computed tomography, acoustical imaging has the advantages of low-cost, portable and fast in both data acquisition and image reconstruction. To get high image resolution while take into account the high attenuation of ultrasonic wave in the materials at high frequency, focus and wideband ultrasonic transducer operating at 20MHz was employed. A robust algorithm to reconstruct the surface objects representing the interface reflection (interface contours) from volumetrically scanned data of the materials was developed, permitting the visualization of material internal structure and possible defects of different types (delamination, crack, rupture) and natures (size, shape...)

Two types of the structural materials, i.e. a 2D textile composite and a porous bone sample were used for testing. The composite imaging shows the textile geometry (bonding ply, fiber bundle and braided architecture) with impact damage defects. For the porous cortical bone sample, the

pore structure can be observed. The quantitative determination of the porosity needs to be further studied.

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