

ULTRA-FAST ULTRASONIC INSPECTION FOR AERONAUTICAL COMPOSITES USING PAINTBRUSH ACQUISITIONS AND DATA PROCESSING ON GPU

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Abstract. The increase in surfaces to be inspected in aeronautical manufacturing augmented by the use of more and more complex parts and materials such as composites stimulates researches to keep NDT costs in manufacturing within an acceptable range. New in-plant inspection scenarios have to be imagined to optimize throughputs. This paper presents development in that direction which allow for optimal use of parallel ultrasonic devices for high speed scanning of large surfaces using the so-called paintbrush acquisition mode. The counterpart resolution loss is compensated by implementation of the Time Domain Topological Energy (TDTE) data processing which is efficient with this kind of acquisitions and compatible with composite materials applications. Implementation on GPU architectures dramatically speeds up the reconstruction operation, opening doors for application in industrial contexts.

Introduction

New generation civil aeronautics structures integrate more composite materials than ever, including large panels. Considering this increase in composite surfaces to be inspected in manufacturing, the amount of time dedicated to NDT in the manufacturing cycle is a crucial issue for programs efficiency. Phased arrays sensors bring powerful technology but are generally not used in an optimal mode regarding inspection rates.

The traditional trade-off between fast acquisition and fine resolution might be broken using phased array technologies combined with appropriate signal processing. In particular the so-called paintbrush acquisition mode offers both very fast scanning and richness of information. Recorded data are rich but have a poor spatial resolution in their raw format, hence needing smart signal processing.

Previous studies on reconstruction techniques from ultrasonic data have shown [1,2] the interest of using the so-called Time Domain Topological Energy (TDTE) method for application to ultrasonic data acquired on composite materials. The TDTE is an adjoint technique for which it can be shown [1] that the adjoint problem is the time reversal operation [3] of the residual signals corresponding to the defect(s) contribution to the ultrasonic response. Besides, theoretical researches [4] have brought rigorous mathematical justifications of such time domain inverse method. In [2] a comparison with the classically used Total Focusing Method (TFM) which performs synthetic focusing (SAFT-like) for phased arrays data has highlighted the interest of the TDTE in terms of separation power and signal to noise ratio in composite parts. The latter article also pointed the counterpart in terms of computation time and stated that the TDTE was currently facing this issue for potential industrial use.

Since then studies have been ran on acceleration of the processing associated to the TDTE method. In particular the emerging of General Purpose Graphical Processing Units (GP-GPU) technology has brought a new light on this kind of processing and opens doors for implementation in industrial diagnosis tools such as U-LIS (NDT-KIT) [7] in a mid-term.

In the first two sections of this paper we respectively introduce the paintbrush acquisition mode and the TDTE reconstruction processing. In the third section a general inspection scenario for ultra-fast NDT of large composite parts, from acquisition to diagnosis, is presented. Finally section 4 presents some results obtained with a prototype implementation of TDTE on GPU from paintbrush data on a linear array.

1. The “paintbrush” acquisition mode

The paintbrush acquisition mode is the quickest way of scanning a part with a given probe. This acquisition mode consists in transmitting once with all the elements of an array and receiving elementary signals in parallel on all the elements of the array [8] (Figure 1).

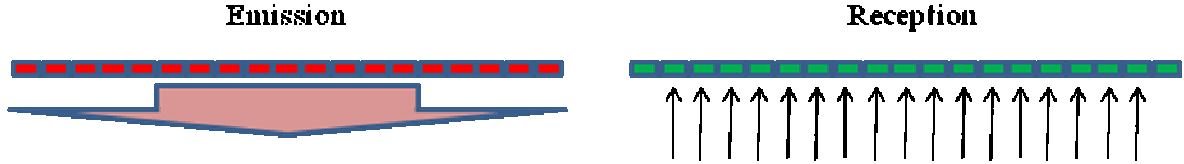


Figure 1: Principle of the paintbrush acquisition mode

This mode allows for optimal acquisition rates since no electronic sweeping is needed at emission neither at reception. A gain of a factor 2 to 6 in scanning time has been demonstrated on a set of parts in industrial conditions, with linear arrays of 64 elements. The more elements there are, the larger the gain is. Its main drawback is the poor resolution in the raw format of the output data. This poor resolution is mainly due to the large aperture when transmitting and receiving. Typically “moustaches signatures” are observed on paintbrush B-scans (Figure 2) instead of well resolved spots in the case of electronic sweepings.

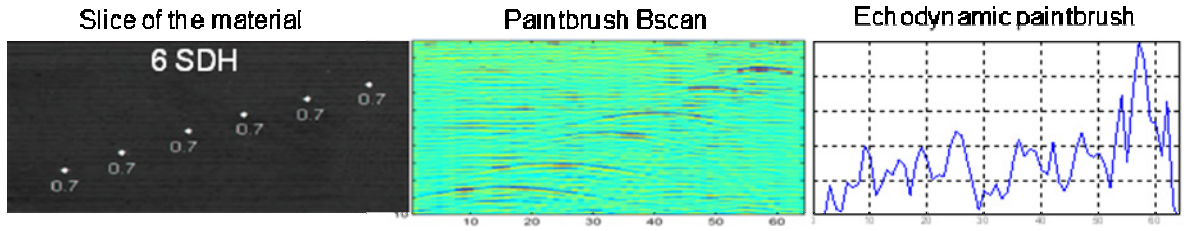


Figure 2: Typical defect signature with paintbrush acquisitions

However the gathered information is very rich in the time-space plane and may be beneficial to an appropriate signal processing.

2. The Time Domain Topological Energy reconstruction technique

Principle of the TDTE method

This method, deriving from a shape optimization approach [9], has been presented in [1] for application to imaging from time domain ultrasonic data. It has been shown that the algorithm is finally a two steps process which realizes a spatio-temporal correlation of a direct field which is the displacement field corresponding to the emission of the probe in the safe medium, and an adjoint field which is the time reversal operation of the defect(s) signature inside the safe medium.

For a given probe position the TDTE algorithm is as follows [12]:

1. Measurement on a reference (safe) medium
→ Get $s_0(t)$ the reference signals on the elements of the probe array
2. Simulation on the reference (safe) medium
→ Get $u_0(\underline{x}, t)$ the reference displacement field at points $\underline{x}$ in the part
 $\underline{x}$ denotes (x, y) in 2D and (x, y, z) in 3D

3. Measurement on the inspected part
→ Get $s_m(t)$ the signals to be analyzed, on the elements of the probe array
4. Time Reversal simulation of the source signals $(s_m(t) - s_0(t))$ applied at the probe array (realizes the back-propagation of the defect(s) signature(s))
→ Get $v_{TR}(x, t)$ the back-propagated (Time Reversed) displacement field at points x in the part
5. Computation of the “topological energy” g_0 as the convolution of the fields $u_0(x, t)$ and $v_{TR}(x, t)$ on the inspected area (x represents the spatial position of a pixel - voxel in 3D - of the probed medium)

$$g_0(x) = \int_0^T \|u_0(x, t)\|^2 \cdot \|v_{TR}(x, T - t)\|^2 dt$$

Notices:

- Measurement and simulation (items 1 and 2 of the algorithm) on the reference (safe part) can be done once for all and stored in the computer memory.
- Basically the measurement results $s_m(t)$ and $s_0(t)$ are made of elementary A-scans.

The originality and the interest of the method is that the time reversal operation is made numerically on the basis of ‘really’ recorded signals and thus does not require to perform it experimentally and to have a time reversal electronic device. Acquisition is then not slow down and scanning can be made at high speed.

GPU implementation of the TDTE algorithm

The previous paragraph has shown that the reconstruction algorithm is based on the simulated back-propagation of the defect(s) signature(s) inside the reference, safe, medium. This step constitutes the major cost of a TDTE reconstruction since it considerably exceeds the time needed to compute the convolution step. Therefore major efforts for processing time reduction have been put on reducing the simulation time for the adjoint field computation. We have originally chosen to perform the adjoint field simulation using a Finite-Difference in Time Domain (FDTD) code which has the advantage of being able to account for complex anisotropy configurations such as one can find in composite materials [13].

Today graphic cards typically intended to 3D games are being used for scientific computation as massively parallel computing support. The idea is to use the very high number of processing units of graphical cards (GPU) to perform unitary operations (plus, times,...) massively in parallel and therefore greatly accelerate the global computation. Besides such cards are now very cheap, are compatible with standard personal computers, occupy little space, and can run under classic operating systems such as Windows or Linux. However the final performance benefit of using GPU for scientific computation strongly depends on the algorithm to be implemented. This kind of architecture is particularly powerful for ‘pixel-wise’ processing which is, to some extent, the case for FDTD computations [14].

The material we have used is an ASUS ENGTX295 card with 2-GPU NVIDIA GeForce GTX 295 chipsets, having in total 480 ALUs (arithmetic-logic-units).

NVIDIA CUDA has been used for coding [15]. CUDA is a C-like programming language which allows for programming on GPGPU (General Purpose GPU). CUDA provides three main elements for software programming: a CUDA driver, a CUDA C compiler and a small set of scientific libraries (CUBLAS & CUFFT). CUBLAS and CUFFT are two libraries provided by NVIDIA. They are the CUDA analogues of the classic BLAS (Basic Linear Algebra) and FFT libraries.

CUDA applications can be portable and run on any CUDA enabled graphic card.

Three major optimizations using GPU have been performed on our prototype implementation of TDTE:

- Porting the FDTD algorithm on CUDA
- Porting the convolution operation on CUDA

These two first items are the direct porting of the CPU version to a GPU support. The third improvement consists in

- Implementing a semi-analytical solving of the ultrasonic propagation in the coupling medium on CUDA by numerical computation of the Rayleigh integral (Figure 3)

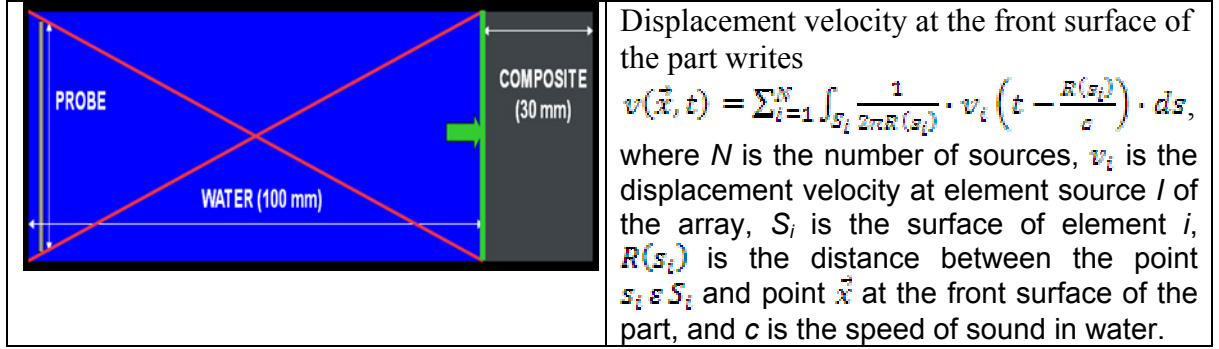


Figure 3: semi-analytical solving in the coupling medium

We will see in section 4 that final performances are dramatically improved by using GPU, but also that this last item is very important. Indeed if using GPU enables great acceleration of FDTD computations, the fact to not compute FDTD in the coupling medium (which has no interest for the reconstruction) remains the most efficient way of acceleration.

3. Scenarios for fast acquisitions and accurate diagnosis

In the aeronautical manufacturing phase, a critical time for NDT operations is the time during which the structure part is “locked” for inspection. Another major issue is the time needed to put a diagnosis on the inspected part. The first issue can be addressed using phased arrays and their power to cover wide areas in a minimum of scanning paths in the paintbrush mode. Elements to address the second issue have been presented in the previous paragraph.

Figure 4 gives two pictures of scenario for fast inspection of large surfaces. The two figures only differ by the nature of the array which is used for inspection. However the kind of array influences the kind of reconstruction processing to be done and also the nature of the output of the processing.

On Figure 4 (a) a 1D array (linear) is considered. Using data from this type of array we are able to apply reconstruction for each position of the array. Typically we have 2D reconstructions for each position of the probe. Possible output is then a slice by slice definition of the defect, sometimes called 2.5D description.

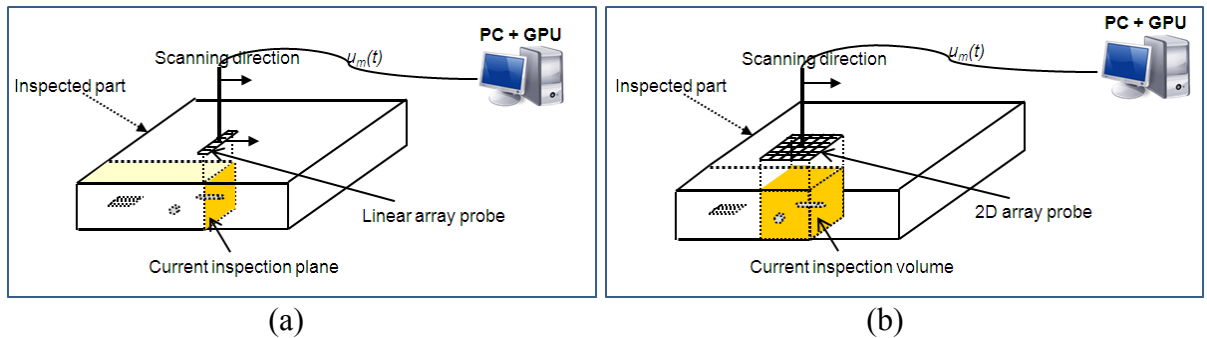


Figure 4 – Paintbrush acquisition & data processing on PC with GPU.

(a) linear array → 2.5D reconstruction (by slice),

(b) 2D array → 3D reconstruction

On Figure 4 (b) the example of a 2D array is considered. Using data from this type of array we are able to apply reconstruction for each position of the array, but for each position we may have a 3D description of the medium under the probe. A particularly interesting 2D array configuration for this application is described in [17].

For efficiency sake, reconstruction should not be launched for every scanning position of the probe. Then reconstructions are run only for probe positions for which some anomalous signal indication is recorded.

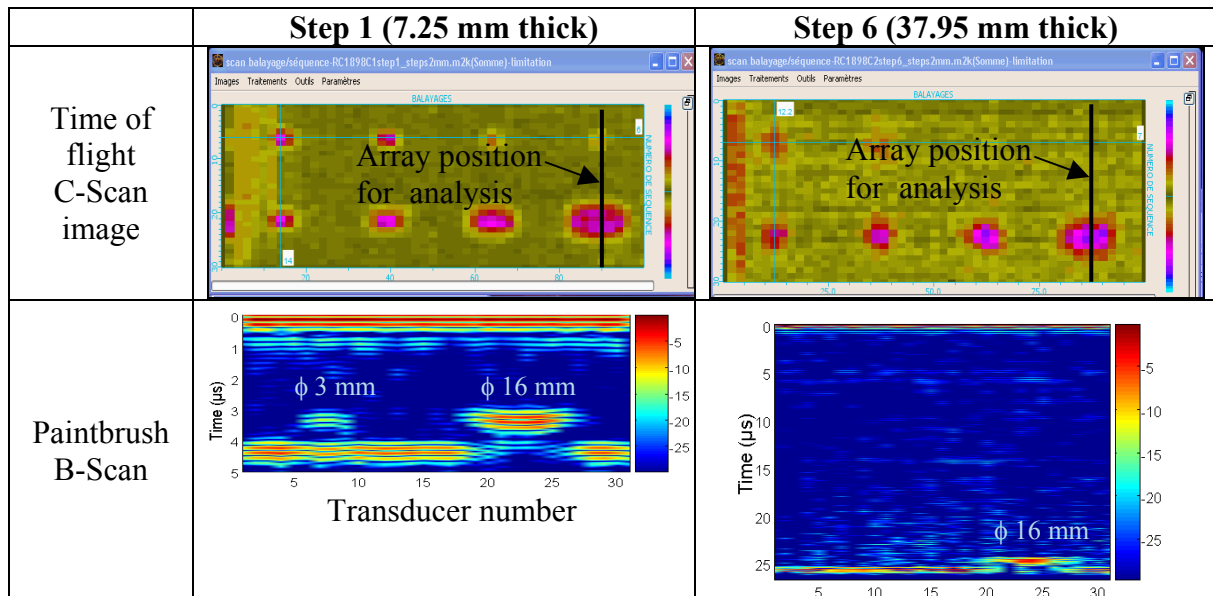
This approach leads to outputting cartographies with different levels of resolution. It is like a coarse picture which can be refined in selected areas.

On the principle, applying the TDTE in post-processing is like realizing a computed “a posteriori focusing” using the full information (signal coherence in space and time) provided by the paintbrush acquisition. It results in enhancing the resolution for sizing, a bit like a complementary inspection using focused probes would do.

4. Results

Reconstruction results on composite

The TDTE reconstruction algorithm has been applied to acquisitions performed with a 32 linear elements array (nominal frequency 3 MHz) on a stepped composite material reference blocks containing flat bottom holes (FBH) at each step. Reconstruction results are presented on Figure 5. The B-scan used for analysis is the one corresponding to the position of the probe above FBH $\phi 3\text{mm}$ and $\phi 16\text{mm}$, as depicted on Figure 5. Figure 5 (left) is for the step 1 of the reference block (7.25 mm thick), and Figure 5 (b) is for the step 6 (37.95 mm thick), so that we cover the easiest (thinner) and worst (thicker) configurations.



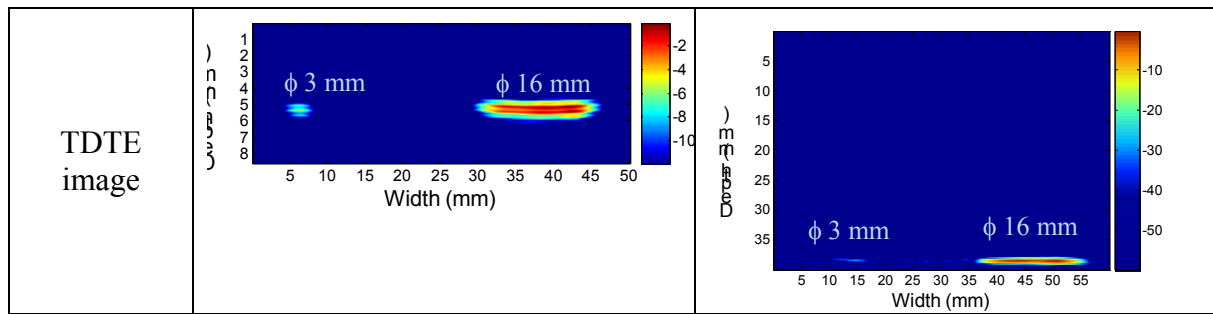


Figure 5: TDTE reconstruction of FBH $\phi 3\text{mm}$ and $\phi 16\text{mm}$ on step 6 (37.95 mm thick)

We observe that processing with TDTE results in an improvement of the signal to noise ratio and in an increase in resolution for the FBH sizing. The reconstruction of the FBH $\phi 3\text{mm}$ on the 37.95 mm thick step is particularly noticeable. For this latter FBH, C-scans and B-scans show nothing above the noise while the TDTE reconstruction makes it appear due to the coherent combination of low amplitude signals at the FBH $\phi 3\text{mm}$ location.

Figure 6 gives elements of understanding on how the TDTE can reconstruct the FBH $\phi 3\text{mm}$ while the recorded B-scan seems to have no indication about it.

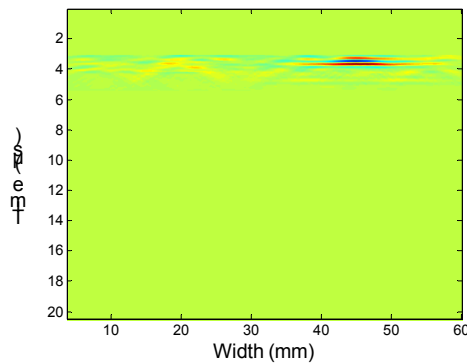


Figure 6: Back-propagated signals at the front surface of the part. Displayed at the time scale used for back-propagation, the signals from the FBH $\phi 3\text{mm}$ form a coherent signature which then focuses at the FBH location when resuming the back-propagation.

Looking at the signals after back-propagation until the front surface of the part, one sees that a coherent signature of the FBH clearly appears. Although appearing at low amplitudes, the signature is remarkable because of the coherence in time of the elementary signals. These coherent contributions focus at the FBH location after full back-propagation, thus highlighting the FBH. Application of the spatio-temporal correlation step of the TDTE then provides the image of Figure 5 on which the FBH $\phi 3\text{mm}$ is reconstructed.

Table 1 shows quantitative comparison of SNR and sizing at -6dB for the traditional technique (analysis on paintbrush B-scan or C-scan) and for the TDTE processing.

		Paintbrush B-scan		TDTE processing	
		FBH $\phi 3\text{ mm}$	FBH $\phi 16\text{ mm}$	FBH $\phi 3\text{ mm}$	FBH $\phi 16\text{ mm}$
SNR	Step 1	9.4 dB	17.9 dB	13.4 dB	18.0 dB
	Step 6	0 dB	12.2 dB	7.6 dB	35.5 dB
Sizing @ -6dB	Step 1	6 mm	14 mm	4.2 mm	15.2 mm
	Step 6	Not detected	11 mm	3.3 mm	14.5 mm

Table 1 – SNR and sizing comparisons between raw data and processed TDTE data

This table shows that TDTE always improves the SNR and refines the sizing. Improvement is particularly noticeable for the step 6.

Processing time improvement with the optimized GPU implementation

Table 2 presents the improvements in terms of processing time after GPU implementations described in paragraph 2.

	All FDTD on CPU	Rayleigh in the water on GPU + FDTD in the part on CPU	Rayleigh in the water + FDTD in the part. All on GPU
Step 1 (7.25 mm depth)	2h50mn = 10200 s	8mn12s = 492 s	45 s
Step 6 (37.95 mm depth)	8h36mn = 30960 s	2h20mn = 8400 s	600 s

Table 2 – TDTE processing time comparisons showing improvements from the initial CPU implementation

The processing time is dependent on the total number of pixels (voxels in 3D) of the area to image. This depends on both the surface (and volume) of the part to be imaged and the resolution (size of pixel of the image). This explains the big difference in processing time between the step 1 and 6, since the same resolution has been applied for the two.

These impressive improvements in processing time (factor 225 for step 1 and 52 for step 6) are due to:

- application of semi-analytical computation in the water path (from CPU to “CPU+Rayleigh on GPU”)
 - speed-up of a factor 21 for step 1
 - speed-up of a factor 3.7 for step 6
- massive parallel computing on GPU (from “CPU+Rayleigh on GPU” to “Rayleigh + GPU”)
 - speed-up of a factor 11 for step 1
 - speed-up of a factor 15 for step 6

The speed-up factor due to semi-analytical computation in the water is less for step 6 because the water path is constant (25 mm) while the depth of the material is not (from 7.25 mm for step 1 to 37.95 mm for step 6). Yet the higher the ratio “water path/CFRP depth” the better the speed-up factor due to semi-analytical computation in the water.

Conclusion

Scenarios and tools to reduce NDT throughputs in aeronautical manufacturing of large composite parts have been presented. It consists in acquiring ultrasonic data using phased arrays in the paintbrush mode and processing the acquisitions with the Time Domain Topological Energy (TDTE) method in case of indication. The TDTE allows for fine characterization of the defects from paintbrush data. A first prototype of TDTE processing on GPU has been implemented and first evaluations have been made and compared with results on paintbrush data. It shows great improvement by use of TDTE both on signal to noise ratio and sizing accuracy. Computation times have been decreased by factors from 52 to 225, depending on the thickness of the composite part. Such first results lead to very encouraging perspective for implementation in industrial contexts.

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