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Published in:
Procedia C I R P

DOI:
10.1016/j.procir.2016.10.125

Publication date:
2017

Document version
Publisher's PDF, also known as Version of record

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Citation for pulished version (APA):
Kappatos, V., Asfis, G., Salonitis, K., Tzitzilonis, V., Avdelidis, N., Cheilakou, E., & Theodorakeas, P. (2017). Theoretical assessment of different ultrasonic configurations for defects detection in composite components. Procedia C I R P, 59, 29-34. DOI: 10.1016/j.procir.2016.10.125

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 59 (2017) 29 – 34

www.elsevier.com/locate/procedia

The 5th International Conference on Through-life Engineering Services (TESConf 2016)

Theoretical Assessment of Different Ultrasonic Configurations for Delamination Defects Detection in Composite Components

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Abstract

It is well known that structures' safety is crucial and of great importance. Part of their maintenance procedure is structural inspection, which is currently performed with the aid of Non Destructive Testing techniques, aiming to detect structural defects in damaged or flawed components and prevent a catastrophic failure by substituting or repairing them. The objective of this work is the theoretical assessment of different ultrasonic configurations that could maximize delamination defect detection in composite components. Modeling study was performed using simulation software, where physical models representative of laminated Carbon Fiber Reinforced Polymer composites, consisting of a variety of artificial delamination defect modes (different sizes and depth), were numerically tested. Different ultrasonic configurations on both the positioning and the firing of the probe's elements including Phased Array delay timings and sampled array techniques were investigated and are presented in this paper. The potential of Full Matrix Capture data acquisition technique, modelled here, along with the post processing Total Focusing Method reconstruction approach is also assessed in terms of their ability to enhance defect detectability and visualization.

Peer-review under responsibility of the scientific committee of the The 5th International Conference on Through-life Engineering Services (TESConf 2016)

Keywords: Ultrasonic; Assessment; Sensor Configuration; Phased Array; Composite.

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1. Introduction

A composite material is a material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different from the individual components. The individual components remain separate and distinct within the finished structure. The new material may be preferred for many reasons: common examples include materials, which are stronger, lighter, or less expensive when compared to traditional materials. Composites are used in wide variety of markets, including aerospace, architecture, automotive, energy, construction, military, etc. [1].

Along with this outbreak in the use of composites, a number of Non-Destructive Testing (NDT) methods have been further developed especially for composites. Except from the visual inspection, which is very common in some industries many other methods like Thermography, Radiography, Acoustic Emission, Eddy Current and Ultrasound have been investigated and used for inspecting composites. The applicability of different NDT inspection techniques will vary each time, according to the part size, shape and material [2].

Ultrasonic Testing (UT) is a well-established technique based on the vibration of materials, which generally referred to as acoustics. The inspection of CFRP components with UT is subject to very challenging requirements in terms of ensuring a reliable and time efficient NDT. The main technical difficulties associated with UT in homogenous materials are the attenuation, scattering and absorption of the signal and shadowing effect of multiple damages. Many of those difficulties can be overcome using Phased Array

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doi:10.1016/j.procir.2016.10.125

Ultrasonic Testing (PAUT), which is one advanced UT method. The PAUT probe consists of many small ultrasonic transducers each of which can be pulsed independently. By varying the timing, for instance by pulsing the elements one by one in sequence, a pattern of constructive interference is set up those results to a beam at a set angle. With the possibility to control parameters such as beam angle and focal distance, this method is very efficient regarding defect detection and the speed of testing. But in-homogenous materials such as multi-ply composite structures are inherently anisotropic resulting in varying UT wave propagation speed per angle. Thus, the main motivation of this work was to assess the possible advantages of advanced UT techniques as they are offset due to the effects of anisotropy in composite structures. Another very interesting set of techniques is the sampled array imaging with Synthetic Aperture Focusing Technique being the most used in multichannel detection systems since the 1950s [3]. The main difference with Phased Array (PA) techniques is that they do not fire a salvo of pulses on different elements in accurately synchronized phase delays (transmit beam forming) but fire one element at a time and record the response received in some or all elements. This firing sequence when all receive elements are recorded is known as Full Matrix Capture (FMC) with the matrix describing all the combinations of transmit and receive elements of an array with a size of NxN with N being the number of array elements.

Taking advantage of wave superposition, the matrix of received A-Scans can undergo any receive beam forming and allows recreating images focused at any given point of the area tested by the probe. But more importantly, instead of imitating a PA firing, the A-Scans can be spatially selectively summed in order to recreate an image that is fully focused at all its points at the same time.

This has been known as the Total Focusing Method (TFM) from Bristol University’s paper [4] that first described the use of the method in industrial ultrasonic NDT. The technique suffers a lot when used with non-homogeneous and anisotropic materials as the beam paths can be distorted and the sound propagation speed varies per path. REverse PHAse MATching (REPHAMAT) is an algorithm proposed by Pudovikov et al. [5] to cope with this problem when inspecting dissimilar welds. Unfortunately, it relies on the fact that depending on "joint type, heat abstraction, and gravity force" and other welding parameters, an "inhomogeneous anisotropic structure with characteristic texture arises". This is far from the case of the inhomogeneity found in composite materials that due to their manufacturing method is of a mostly stochastic nature.

The effectiveness on all the above NDT methods is based on how good is the signal output (SNR level, crosstalk etc.). That is the reason that a good amplification of the received signal is needed. Time Reversal is a signal processing technique for focusing waves. Time Reversal Mirror (TRM) has been used for decades in the optical domain and in the ultrasonic domain it was initially introduced by Mathias Fink [6]. The TRM theory is based on the reciprocity of the wave equation when expressed for linear, low noise and low attenuative media. The time reversal, in other words the negative time of the received signal, is also a solution of the wave equation. If the original signal is a delta function (Dirac), the received signal is the impulse response of the channel (by channel naming the system of the transducer and of the propagating medium). Through TRF method, a reversed version of the impulse response function is sent back in the channel, creating effectively an autocorrelation function with a peak at the origin where the source was. A different way to think of a time reversal experiment is that TRF is a "channel sampler". The TRM measures the channel during the recording phase, and it uses this information in the transmission phase in order to optimally focus the wave back to the source. A significant number of research studies dealing with the application of TRF method for the inspection of composite materials can be found in the literature. Sohn et al. proposed a wavelet based time reversal method for the detection of internal defects in composite materials [7], while Qiu et al. evaluated the potentiality of this approach for impact imaging in complex shape aerospace composite components [8]. Many work has been done in the describing the different PA methods and different modeling approaches has been studied. Several PAs techniques for damage detection are presented and how array configurations affect the resolution and directionality [9]. In [10], 2D phased sensor array configurations are evaluated in thin film panels. A systematic way, calculates the 3-D radiation patterns produced by phased array transducers, is presented in [11]. Theoretical simulations of the pulse-echo beam of two-dimensional phased array were conducted in [12]. The work, presented in this paper, takes the above research one step beyond by assess different PA ultrasonic configurations to provide the best one for the defect detection. This assessment will deliver a modelling tool to decide the best possible PA array for the given composite structure.

The scope of this work is to present the theoretical assessment of different PA ultrasonic configurations that could maximize delamination defect detection in composites. The PA ultrasonic modeling was performed using the commercial software CIVA [13], where physical models representative of laminated Carbon Fiber Reinforced Polymer (CFRP) composites, consisting of artificial delamination defect modes (different sizes and depth), were numerically tested. Different ultrasonic configurations both on the positioning and on the firing of the probe’s elements were investigated and are presented in this paper.

2. Different Modelling Approaches

Various approaches can be used when attempting to model wave propagation, all but simple ray tracing involve solving partial differential equations. In free space, the analytical solution of the wave equation can be used, but as soon as even simple boundaries are included problems arise. The Finite Element Method (FEM) is nowadays one of the most popular modelling approaches in structural mechanics and acoustics. The FEM solution process follows 4 simple steps [14]: i) Divide structure into pieces (elements with nodes) (discretization/meshing), ii) Connect (assemble) the elements at the nodes to form an approximate system of equations for the whole structure (forming element matrices), iii) Solve the system of equations involving unknown quantities at the nodes, iv) Calculate desired quantities (e.g., strains and stresses) at selected elements. The main drawback, which becomes even greater in wave propagation simulations, is that the equations have to be solved at all the nodes of the system. Semi- analytical methods on the other hand offer the advantage of computing the solutions to the equations only at the boundaries. Only the boundaries are discretized resulting in a much smaller total number of nodes. This comes at the expense of accuracy but offers a significant increase in solution speed.

In this paper, modeling investigation was carried out using the CIVA simulation software. CIVA simulates the ultrasonic beam field which is radiated by a probe can be simulated in CIVA using a semi-analytical ray based model [15]. This model relies on a high-frequency (frequency for which the wavelength is small with respect to characteristic dimensions of the model) approximation method that uses an asymptotic solution of the elastodynamic equation. It is applicable to complex structures provided that the configuration does not vary rapidly with respect to the wavelength [16]. The shape, size and material of the part to be inspected as well as the parameters of the inspection equipment such as ultrasonic transducer size, shape, element number, pitch the position of the inspection equipment in relation to the part were defined.

3. Modelled Sample and Probes

To setup a model using CIVA, the user can either choose from 7 pre-existing sample shapes or create their own cylindrical or planar extrusion of a CAD created profile. The sample material can be chosen from a large variety of isotropic or anisotropic materials and composites. New materials can be added easily in the database by defining the velocity and density; attenuation is given for several database materials and can be defined for any new ones. Several types of flaws are already defined in CIVA, where all the user needs to do is specify the dimensions and location. For more complex flaw modelling, it is also possible to create multifaceted and CAD contoured planar flaws. Once the inspection parameters are defined, the user can calculate the defect response, or if they prefer, first model the beam profile to verify that the beam is angled and focused in the part as expected [17]. The type of wavemodes included in the calculations can be chosen along with response model for the flaws [13].

The numerical simulations performed in this work were focused in using models of representative laminated CFRP composite samples, containing a variety of delamination defects. Delamination was modelled as a material, discontinuity; incident elastic waves are reflected without any percentage of the energy passing through. In cases that the wavefront is larger than the delamination or only part of it incident to the delamination, some percentage of the energy is reaching beyond. The modelled sample geometry description, material characteristics, size depth and type of the included flaws in the sample are summarized in tables 1 and 2.

Table 1 Description of sample.

Fibre Material	Num. of Plies	Thick.	Dimen.	Structure lay-up
CFRP Laminate	16	≈ 2.5mm	200x 200mm	(0,+45,-45,90, 90, +45, -45, 0)2s

Table 2: Delamination defect description and characteristics.

Defect	1	2	3	4	5
Disconti-nuity type	Delamination	Delamination	Delamination	Delamination	Delamination
Defect size (mm)	5x5	ø10	8x5	ø7.5	9x15
Location / depth (mm)	1st ply / -0.16	2nd ply / -0.32	3rd ply / -0.48	6th ply / -0.96	12th ply / -1.92

The main reason for choosing CIVA to perform the simulations in this work was that it offers the user the ability to “homogenize” a composite material using basic information of the manufacturing method and materials. The purpose of homogenization is to simplify the properties of the composite medium by reducing it to a homogeneous equivalent with simple elastic constants. Single layer composites can be defined using as parameters: i) The individual fibre diameter, ii) The overall fibre density, iii) The fibre and epoxy material stiffness matrixes and attenuation coefficients.

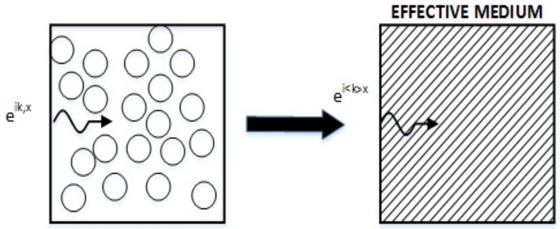

Fig. 1. Homogenization process.

The layer then is homogenized as a transversely isotropic continuous material using Yang and Mal’s algorithm [18]. Furthermore, multilayered composites can be homogenized as Orthotropic from a series of plies by inputting the ply thickness and each ply’s fiber orientation angle. Briefly speaking, this method consists, for a given angle of incidence, of tracing the direction of the ray path’s energy as it propagates through the multilayer structure, then synthesizing the equivalent slowness curves on the basis of the orthogonality between slowness surfaces and the direction of energy rays [19].

A large variety of transducers shapes, sizes and types can be modeled by CIVA, including single element, dual element or PA probes (linear, matrix and flexible arrays). Both single element and PA probes can be modeled in either contact or immersion conditions. These probes can either be flat or focused. Water and oil are the two couplant choices already in the software, but it is easy to add additional materials such as glycerin based gels. When a transducer is mounted on a wedge, the user defines the wedge dimensions, angle and wedge material.

In this study, two different probes were modeled, the first being a single element 5MHz probe and the other was a linear array wheel probe of 64 elements with 5MHz central frequency and a pitch of 0.8mm. Both probes were unfocused (flat) and normal to the inspection surface in an immersion configuration, the couplant was considered as water and no wedges were used. These properties were chosen from past experience of working with composites and so that they are close to potential mass production array probes from major manufacturers [20]. Since a fully bespoke array probe is a rather costly piece of equipment it is better to search for of the shelf solution and go for custom made items only if they prove inadequate. Both probes were simulated without any geometrical focusing and the input signal was a Gaussian pulse at the probes' central frequency.

4. Modelled Ultrasonic Configurations

The two probes mentioned above are used in order to model three distinct configurations: i) traditional immersion tank UT scanning and uses the single element probe, ii) a typical PAUT scan with a wheel probe, and iii) the same hardware as the second but fires it in FMC configuration. Detailed descriptions of the two hardware setups for the first and second/third configuration cases are provided below.

4.1. Immersion UT

In this configuration a single element probe was used which mechanically scanned the sample in two axis in a raster pattern having a resolution of 1mm. The probe was set at a distance of 85 mm over the sample. Immersion tank C-Scan is the industry standard for the best quality of ultrasonic scans that one can achieve.

4.2. Phased Array Linear Electronic Scan

This configuration includes the utilization of the array probe and the set-up of PA firings. Due to the non-isotropic nature of composite materials a small size, 16 elements, was used for the active aperture. The delays were programmed such that a 0-degree beam, focused at the center of the sample's depth was fired. The delays then were moved along the aperture so that successive batches of 16 elements were fired. This is commonly known as the linear electronic scan configuration. In our case, the firings were also programmed so that the step between two successive shots was effectively not one element, but half. This was achieved by adding shots with 17 active elements instead the standard 16. The range of elements used in successive shots with one element step would be 1 to 16, then 2 to 17, 3 to 18 and so on, while with the half step technique these were 1 to 16, 1 to 17, 2 to 17, 2 to 18, 3 to 18 and so on. The half step configuration was applied in order to achieve a higher resolution. Furthermore, a distance of 28 mm from the sample was selected with the interface material as water, to simulate values close to commercially available roller probes.

5. Modelling Results

5.1. Immersion C-Scan Imitation

The numerical C-Scan obtained using a single element probe is demonstrated in Fig. 2 (left).

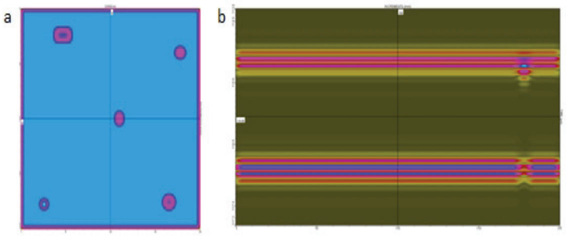

Fig. 2. Single channel immersion testing imitation C-Scan (a), B-Scan of defect in the immersion test (b).

5.2. Linear Roller Probe Half Step

During the solution of these models, a drawback of CIVA was found out concerning the creation of C-Scans from probe movements that span in more than two axes. If the simulated probe is defined with a linear movement along one axis a C-Scan is automatically generated, if a raster or comb scan is defined, the same computation is not straight forward. Thus, seven different models (referred to as "brushes") were run with the probe moving along a single axis. The axes on all models were parallel and the distance of them between consecutive models was equal to the active aperture length. To aid in simplifying presentation, the C-Scan of the first model is presented in Fig. 3 and then using simple image editing the results of all models were combined and can be seen in Fig. 5.

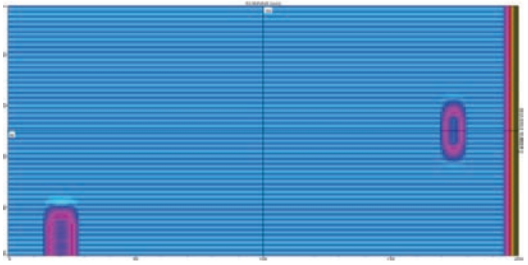

Fig. 3. C-scan of modelled sample, brush 1.

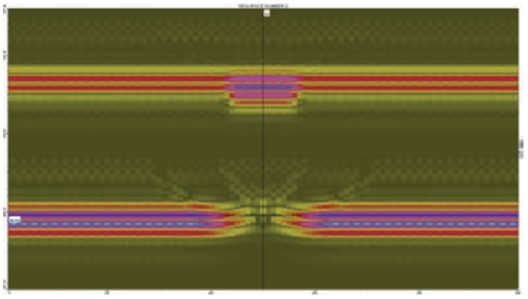

Fig. 4. B-Scan of brush 1 at 50mm (probe movement along the horizontal black line of Fig. 3, cross section over the defect).

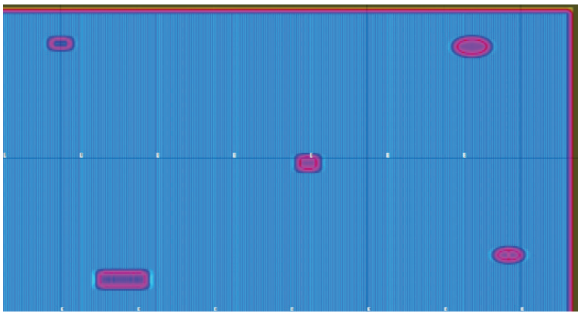

Fig. 5. Combined C-Scan of modelled sample, all brushes.

Contrary to the smooth constant colour of the back wall echo of the immersion model, the PA roller probe models appear to be "ridged". This is expected and is a direct result of the half step configuration used. Since more elements are used in the even shots than in the odd ones the amplitude reflection is a tiny bit different, enough though to change the colour. Comparing the results of the C-Scan with the linear array probe Fig. 5 and the single probe Fig. 2 (a) (Fig 1, (a)), it is obvious that the array probe offers much higher image resolution. That is attributed to the fact that the effective centre of the focal spot has a resolution of 0.4 mm along the active aperture, where the single element is still at 1 mm. In addition, the image was produced instantly whereas the single probe had to move along the length of the aperture.

5.3. Roller Probe FMC

The same strategy described above for the sample with the linear scan was used with the FMC firing as well. The problem encountered here is that although CIVA managed to solve the responses for all scan positions and all shots, it did not offer a batch processing for the reconstruction. Since a total of 1400 different reconstructions would have to be performed before being able to recreate a pseudo C-Scan, it was decided to compare the results by selectively choosing reconstructions over defects.

The results from the TFM reconstructions are better and crispier than the linear scan, but not at a significant extent. The reconstruction zone has to be inside the material so shallow delamination defects are not imaged fully. The deeper defect is imaged much better, but the inherent resolution limit derived from the frequency shows the ultimate limit.

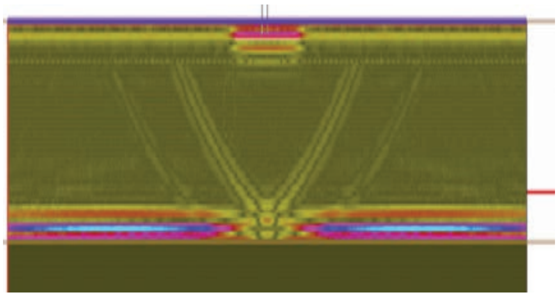

Fig. 6.TFM reconstruction of shallow defect, brush 1 (same as Fig. 2 (b) and Fig. 4).

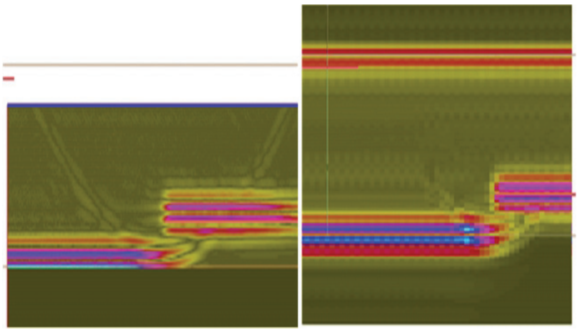

Fig. 7. TFM reconstruction (left) against linear scan (right) of deeper defect, brush 1.

6. Additional Models

Four extra models were executed to determine whether the sample to wheel probe distance used in 5.2 and 5.3 was the optimal one.

6.1. Array Probe 5 and 10mm Waterwedge FMC

It was decided to lower the array probe closer to the sample as in an attempt to have more transmit–receive pairs lying within the array aperture. Two different heights were simulated one at 10mm and one at 5mm.

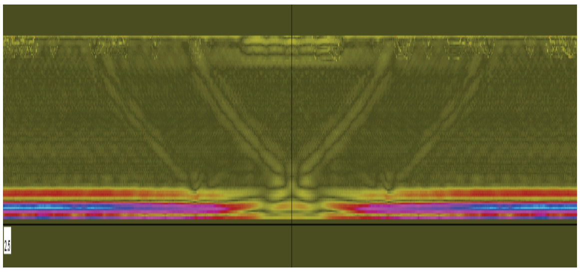

Fig. 8. Array probe at 5mm from sample, brush 1 TFM reconstruction of shallow defect (same as Fig. 2 (b), Fig. 4 and Fig. 6).

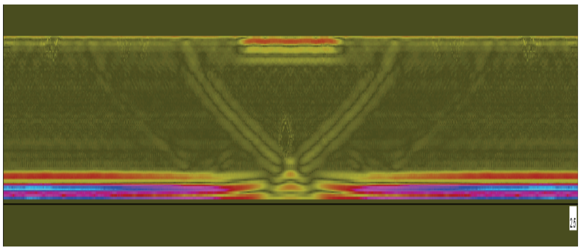

Fig. 9. Array probe at 10mm from sample, brush 1 TFM reconstruction of shallow defect (same as Fig. 2 (b), Fig. 4 and Fig. 6).

The results are not as good as Fig. 6, so the original distance is better to be used. Due to the lower distance the image now was reconstructed using paths that contained higher angle variation. Thus, the difference in speed caused by the material anisotropy adversely influenced the image reconstruction accuracy.

6.2. Array probe 5 and 10mm Waterwedge Half Step

Since the array probe will physically be at a specific distance, we also tried to check the results of linear scan at closer distances to the sample.

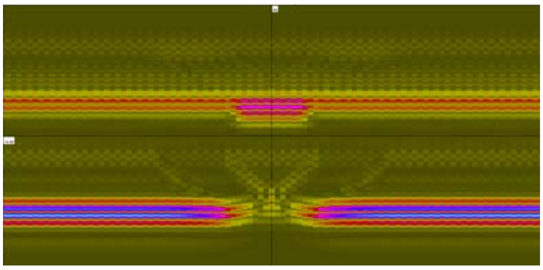

Fig. 10. Array probe at 10mm from sample, brush 1 linear electronic scan of shallow defect (same as Fig. 2 (b), Fig. 4 and Fig. 6).

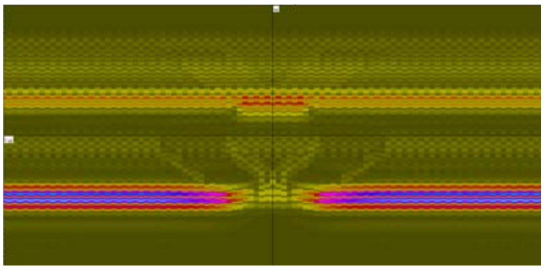

Fig. 11. Array probe at 5mm from sample, brush 1 linear electronic scan of shallow defect (same as Fig. 2 (b), Fig. 4 and Fig. 6).

As with the TFM in the previous section the linear electronic scan results are not as good as the original distance of 28mm. In this case, the attempt to focus closer to the probe did not allow the individual wavelets to interfere enough and deteriorated the focusing quality.

7. Conclusions and Future Work

In this work, different ultrasonic configurations were theoretically assessed through CIVA simulation software aiming to predict the optimum parameters that will lead to the development of a PAUT testing configuration for composite structures inspection.

The numerical simulation results obtained from the PA modelling showed that a linear array probe consisting of 64 elements with a central frequency at 5MHz could provide accurate inspection of the aircraft composite parts specified in this paper. Probe characteristics (i.e. pitch, elevation) close to commercially available solutions seem to provide sufficient resolution and a water edge or roller is considered to be efficient. A halfstep configured linear scan at 0 degrees with 16 elements is expected to provide resolution even better than an immersion C-Scan with a scan resolution of 1mm.

As regards to the TFM post processing reconstruction approach, contrary to initials expectations, the TFM algorithm did not provide a step change improvement in the delamination defect imaging. Nevertheless, it provided images of higher resolution and lower noise than the linear electronic scan. It suffers however from a quite low reconstruction speed as well as from the need to know the underlying sample geometry. Since ultrasonic pulse receivers can acquire multiple firing sequences, the best practice seems to be the utilization of linear electronic scan configuration as a screening tool and then reconstruct with TFM only at the areas that a defect has been identified.

Future work would be to apply the slowness curves of the anisotropic material in the TFM reconstruction calculation. Focus also on practical and experimental investigation so the simulated results will be properly validated. More types of defects in composite components like fibre cracking and impact damages need to be simulated as well. Finally, future work will investigate the quality of the bondline, which are points that are more prone to defects, using UT.

References

[1] Mallick P.M. Composites Engineering Handbook. CRC Press; 1997

[2] Hsu D.K. Nondestructive inspection of composite structures: methods and practice, In: Proc 17th WCNDT; Shanghai; 2008;

[3] Wiley C.A. Synthetic Aperture Radars: A Paradigm for Technology Evolution. IEEE Trans. Aerosp. Electon. Syst; 1985. Vol 21, p 440-43

[4] Holmes C, Drinkwater B.W, Wilcox P.D. Post processing of the full matrix of ultrasonic trasmit- receive array data for nondestructive evaluation. NDT & E Int; 2005. Vol 38, p.p 701-11

[5] Pudovikov S, Bulaninov A, Pinchuk R. Innovative Ultrasonic Testin (UT) of Nuclear Components by Sampling Phased Array with 3D Visualization of inspection reults. Proc 8th JRC-NDE; Berlin; 2010.

[6] Fink M. Time reversl of ultrasonic fields I. Basic principles. IEEE Trans. Ultrason., Ferroelect, Freq. Control; 1992. Vol 39, pp. 555-66

[7] Sohn H, Woo Park H, Law K. H, Farrar C.R. Damage Detection in Composite Plates by Using an Enhanced Time Reversal Method. J. Aerosp. Eng; 2007. Vol 20, pp. 141-51

[8] Qiu l, Yuan S, Zhang X, Wang Y. A time reversal focusing based impact method and its evaluation on complex composite structures. Smart Mater. Struct; 2011. Vol 20, 105014

[9] Yu L, Tian Z. Phased array techniques for damage detection in aerospase structures. Structural Health Monitoring in aerospace strictures; 2016 pp. 285-306

[10] Yoo B, Purekar A.S, Zhang Y, Pines D. J. Piezoelectric paint based two dimensional phased sensor arrays for structural health monitoring of thin panes. Smart Material Structures; Vol 19, 2010, pp 1-17

[11] Sung-Jin S, Chank-Hwan K. Simulation of 3-D radiation bean patterns propagated through a planar interface from ultrasonic phased array transducers. Ultrasonics; Vol 40, 2002, pp. 519-524

[12] Mendelsohn Y, Wiener-Avnear E. Simulations of circular 2D phase-array ultrasonic imaging transducers. Ultrasonics; Vol 39, 2002, p. 657

[13] Civa Soft. In : http://www.extende.com/ultrasonic-testing-with-civa

[14] Lin L. Notes on Introduction to FEM. In: http://www.me.berkeley/edu /~lwlin/me128 /FEMNOTES.pdf . Berkeley Univ, Mech, Eng. Dep.

[15] Gengembre N, and Lhémery A. Pencil method in elastodynamics. Application to ultrasonic field computation. Ultrasonics; Vol. 38, 2000, pp. 495-499

[16] Brokesova J. Asymptotic ray method in seismology, a tutorial, Matfyzpress, 2006

[17] Schumacher E. CIVA; Simulation Software for NDT Applications. Proc NDT in Canada Conf. Ontario; 2009

[18] Yang R, Mal, A. K. Multiple scattering of elastic waves in a fiber-reinforced composite. J.Mech.Phys.Solids; 1994, Vol. 42, pp. 1945-68.

[19] Deydier S, Gengembre N, Calmon P, Mengeling V, Petillon O. Ultrasonic field computation in multilayered composite materials using a homogenization method based on ray theory. Proc AIP Conf; Melville 2005, pp. 1057-64

[20] Sonatest In: http://sonatest.com/products/range/transducers/wheelprobe-range/corrosion.