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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

V. Kappatos[a], G. Asfis[b], K. Salonitis[c,*], V. Tzitzilonis[d], N. P. Avdelidis[e], E. Cheilakou[f], P. Theodorakeas[f]

[a] Department of Technology and Innovation, University of Southern Denmark (SDU), Campusvej 55, DK-5230 Odense M, Denmark
[b] TWI Ltd, Granta Park, Great Abington, Cambridge, CB21 6AL, UK
[c] Manufacturing Department, Cranfield University, Cranfield, MK430AL, UK
[d] Pattern Recognition Group, Wire Communication Laboratory, Department of Electrical & Computer Engineering, University of Patras, Greece
[e] Computer Vision and Systems Laboratory, Department. of Electrical and Computer Engineering, Université Laval, Quebec City (Quebec), G1V 0A6, Canada
[f] Materials Science & Engineering Dept., School of Chemical Engineering, National Technical University of Athens, Zografou Campus, 157 80, Athens, Greece

* Corresponding author. Tel.: +44 1234 758347. *E-mail address:* k.salonitis@cranfield.ac.uk

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.

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