Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 70 (2015) 664 – 667
Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

Application of a Probabilistic Algorithm for Ultrasonic Guided Wave Imaging of Carbon Composites

Jan Hettler[a,*], Morteza Tabatabateipour[a], Steven Delrue[a], Koen Van Den Abeele[a]

[a] *Wave Propagation and Signal Processing, Department of Physics, KU Leuven Kulak, Etienne Sabbelaan 53, Kortrijk 8500, Belgium*

Abstract

The Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID) is a baseline-dependent imaging method. It utilizes a permanent array of ultrasonic transducers that covers the region of interest to interrogate the structure and estimate the presence and location of damage. The method has already proven its capability to detect different types of damage in aluminum plate structures, e.g. cracking or corrosion damage. In the present study, we apply RAPID to inspect carbon-fiber reinforced polymer (CFRP) components for the presence of impact damage and delaminations. In addition, numerical and experimental results of a baseline-free RAPID approach for the detection of nonlinear defects in CFRP will be presented. This modified RAPID draws on the Scaling Subtraction Method (SSM) which is well known from the field of nonlinear ultrasound.

Peer-review under responsibility of the Scientific Committee of ICU 2015

Keywords: ultrasonic inspection; guided wave; imaging; CFRP; delamination

1. Introduction

Ultrasonic guided wave imaging (GWI) represents a promising competitor for the conventional phased array (single element) UT inspection of CFRP. The main advantage is that GWI can be utilized to interrogate large areas with a limited number of transducers in a very short time.

Unlike classic ultrasonic methods that make use TOF or attenuation, the centre point of the RAPID method is the Signal Difference Coefficient (SDC). By using the signals from an ultrasonic sparse array, obtained before and after damage, and deriving the mutual SDC values between the transducers in the array, damage presence probability in the region of interest can be calculated. RAPID was described in detail by [**?** **?**]. Further improvements of the method were made by [**?**] and [**?**]. So far, most of the experimental work has been done on rather simple aluminium plate structures. The major drawback of RAPID is its sensitivity to the environmental conditions and the corresponding optimal baseline selection. These disadvantages have been partially addressed by [**?**].

RAPID is traditionally a baseline-depedent method. It will be demonstrated, on numerical simulations as well as preliminary experimental measurements, that it can be used for baseline-free inspection. To achieve this goal,

* Corresponding author. Tel.: +3256246209
E-mail address: jan.hettler@kuleuven-kulak.be

Peer-review under responsibility of the Scientific Committee of ICU 2015
doi:10.1016/j.phpro.2015.08.072

nonlinear elastic wave phenomena and appropriate processing and excitation techniques, such as SSM, were employed ([**?**]).

2. RAPID Algorithm

2.1. Conventional RAPID

Conventional RAPID as described by [**?**] utilizes the data from an ultrasonic sparse array consisting of N permanently attached piezo transducers. The SDC for each transmitter-receiver pair in the array is calculated as a first step. The SDC value is basically a measure of the dissimilarity of two specified signals obtained before and after damage. Most commonly, SDC values are calculated based on the correlation coefficient and on the mean square error.

Let the signal transmitted from the array element i to element j be denoted B_{ij} and D_{ij} for the intact (baseline) and damage state respectively. Then the correlation coefficient is defined as

$$\rho_{ij} = \frac{\mathrm{Cov}(B_{ij}, D_{ij})}{\sigma(B_{ij})\sigma(D_{ij})} = \frac{\sum_k (B_{ij}(t_k) - \mu_{ij}^B)(D_{ij}(t_k) - \mu_{ij}^D)}{\sqrt{\sum_k (B_{ij}(t_k) - \mu_{ij}^B)^2}\sqrt{\sum_k (D_{ij}(t_k) - \mu_{ij}^D)^2}}, \tag{1}$$

where $k = 1, 2, ..., n$. n is the number of samples in the signal, t_k is a discrete time (sample index), and μ_{ij}^B, μ_{ij}^D are the mean values of the baseline and damage state signals respectively. The SDC value can then be calculated using ρ_{ij} as

$$SDC_{ij} = 1 - \rho_{ij}, \tag{2}$$

where $i, j = 1, ..., N$. The total number of employed signals is $\frac{N}{2}(N-1)$ if reciprocity is assumed and $N(N-1)$ otherwise. Alternatively, the SDC value can also be calculated as the mean square error between baseline and damage state, i.e.

$$SDC_{ij} = \frac{1}{n}\sum_{k=1}^{n}(B_{ij}(t_k) - D_{ij}(t_k))^2. \tag{3}$$

The inspected area of the sample is then overlaid with a rectangular mesh. The *a priory* probability distribution $s_{ij}(x, y)$ is defined for each transmitter-receiver (TR) and every point $[x, y]$ of the mesh as follows:

$$s_{ij}(x, y) = \begin{cases} \frac{\beta - R_{ij}(x,y)}{1-\beta}, & \text{if } \beta > R_{ij}(x, y) \\ 0, & \text{if } \beta \le R_{ij}(x, y), \end{cases} \tag{4}$$

where β stands for a free threshold parameter that defines the area influenced by one TR pair. $R_{ij}(x, y)$ is the geometrical function defined as

$$R_{ij}(x, y) = \frac{\sqrt{(x_i - x)^2 + (y_i - y)^2} + \sqrt{(x_j - x)^2 + (y_j - y)^2}}{\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}} \tag{5}$$

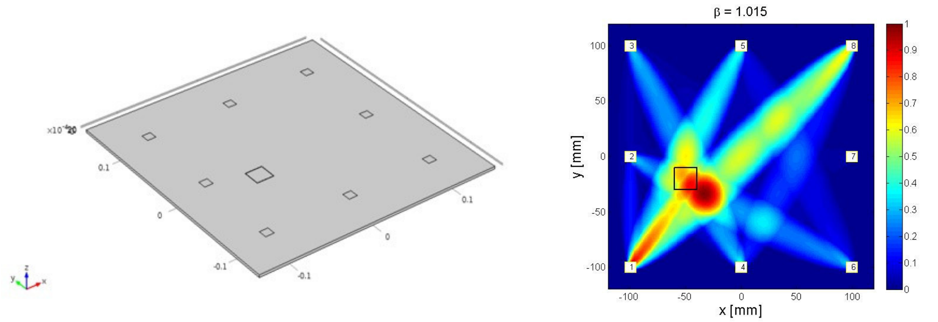
The final probabilistic 2D heatmap $P(x, y)$ that describes the damage presence probability is calculated as

$$P(x, y) = \sum_{i=1}^{N}\sum_{j=1, i\neq j}^{N} SDC_{ij}s_{ij}. \tag{6}$$

2.2. Baseline-free RAPID

We can transform the conventional RAPID into a baseline-free method by introducing the Scaling Subtraction Method (SSM). In this method, a low amplitude excitation signal B_{ij} acts as a reference (defect-free) signal and a high amplitude signal D_{ij} is acquired under the same measurement conditions only with the excitation amplitude upscaled by a factor

$$a = \frac{D_{ex}}{B_{ex}}, \tag{7}$$



(a) (b)

Fig. 1: (a) Simulated CFRP plate (b) Baseline-free RAPID result for a plate with a single nonlinear delamination (kissing bond type defect). Excitation parameters: 20 cycles, Hanning window, f = 50 kHz, scaling factor a = 100. Black box indicates the result for a damaged area. The defect is centered at [-50,-20].

where B_{ex}, D_{ex} are the amplitudes of the excitation signals. The SDC coefficient is then calculated directly using the mean square difference formula as:

$$SDC_{ij} = \frac{1}{n}\sum_{k=1}^{n}(aB_{ij}(t_k) - D_{ij}(t_k))^2. \tag{8}$$

If the inspected system is purely linear, both response signals scale up perfectly and $\mathrm{SDC}_{ij} = 0$. However, if we assume the presence of the nonlinear defect in the interrogated sample, it attains a non-zero value. Using this principle the SDC in (6) can be simply replaced by equation (8) and the method becomes baseline independent.

Numerical simulations were carried out in order to verify the proposed baseline-free RAPID methodology on a simple square CFRP with orthotropic symmetry and a single 20x20 mm nonlinear delamination (Fig. 1a). The defect was simulated as a clapping system (kissing bond) based on the model developed by [**?**]. Figure 1b shows the result of the baseline-free RAPID detection of this nonlinear delamination using only 8 sensor positions.

3. Experiments

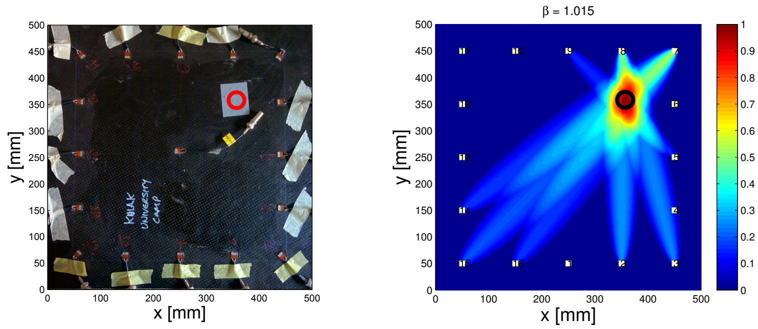
Two experiments were conducted in order to verify the RAPID methodology. In the first one, conventional RAPID was applied to a CFRP plate with an impact damage. In the second one, the baseline-free RAPID was utilized to detect a nonlinear delamination in a smaller and thinner CFRP plate. The same signal generation and acquisition system was utilized in both experiments, consisting of several NI PXI-5122 digitizers, PXI-5412 arbitrary waveform generator, multiplexer and Falco WMA-320 (25x gain) amplifier. PI DuraAct® piezopatches were used to generate the guided waves in the interrogated structure.

The first test sample was a 500x500x8 mm plate made of CFRP. The baseline signals were collected at the ambient room temperature using a square array of 16 rectangular DuraAct® transducers before any damage was produced. Then a 21 J impact was introduced and the data was recollected. Figures 2a and 2b show the original plate and the corresponding damage location as obtained by conventional RAPID.

The performance of the baseline-free RAPID method was tested on a simple 300x300x2 mm CFRP plate laminate with a 20x20 mm delamination (double sided teflon insert) placed at 3/4 of the thickness. The scaling factor for the SSM analysis was a = 18 with B_{ex} = 0.01 V. The image of the array and the resulting baseline-free RAPID image are depicted in figures 3a and 3b respectively.

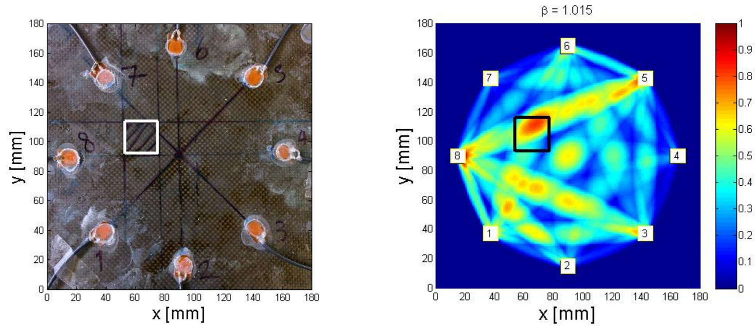
4. Conclusion

It has been shown that RAPID can be utilized to localize the impact damage in the CFRP plate-like structures. Moreover, we have successfully introduced and utilized the baseline-free version of RAPID to detect a delamination



(a) (b)

Fig. 2: (a) CFRP test sample with 16 array elements organized in a rectangular array. The position of the defect is marked with a red circle (b) Conventional RAPID image of the CFRP plate. Excitation parameters: 3 cycles, Hanning window, $f = 50$ kHz, $\beta = 1.015$. The actual defect zone is marked with a black circle.



(a) (b)

Fig. 3: (a) Circular array of transducers attached to a thin CFRP sample. The defect position is marked with the white square (b) Baseline-free RAPID image of the thin CFRP plate. Excitation parameters: sweep $f = 260 - 300$ kHz, duration $t = 100\,\mu s$, Apodized cosine window, $\beta = 1.015$, $a = 18$ with $B_{ex} = 0.01\ V$. The defect zone is marked with a black square.

in a thin CFRP plate. Baseline-free RAPID therefore seems to be a promising evolution of the GWI to localize kissing bond features (simulation) and tiny delaminations in CFRP plates (experiment). This baseline-free RAPID therefore seems to have the potential to increase the sensitivity of GWI inspection approaches to detect nonlinear defects. In order to realize this, further development of the baseline-free method should involve the detection of different types of barely visible damage, and the applicability to the samples with more complex shape.

Acknowledgements

The research leading to these results has gratefully received funding from the European Union Seventh Framework Programme (FP7/2007- 2013) for research, technological development and demonstration under the Grant Agreements no. 284562 (Saristu) and no. 314768 (ALAMSA).