A STATE SPACE APPROACH FOR THE NON-DESTRUCTIVE EVALUATION OF CFRP WITH ULTRASONIC TESTING

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Abstract. The subject of this presentation is a new approach for the evaluation of porosity in Carbon Fibre Reinforced Polymers (CFRP) with ultrasonic testing. The standard procedure for Airbus parts is a pulse echo inspection. This is based on the evaluation of the so-called back-wall echo (BWE), i.e. the echo coming back from the surface opposite to the probe.

However, in situations with complex geometry, like sandwich or bonded parts, this BWE does not exist or cannot be properly evaluated. A new approach is presented based on a “state space” or “phase space” representation of the ultrasonically tested CFRP part regarded as a dynamical system. The final target of the work is to determine a “back-wall echo equivalent” out of the intermediate echoes (that start after the surface echo and end before the BWE). This shall be employable for data from standard commercially available UT equipment that is capable to record full A-scans.

A dynamical system is an (engineering, economical…) system evolving over time, which is represented by its state variables. For a simple system like a pendulum the, in that case 2, state variables are the angle and the angle velocity, which define this system completely. The plane in which the possible values of these two variables are represented is in this case the state space.

A key for evaluation is the reconstruction of the representation in state space via a so-called delay embedding out of one scalar variable. In the present case, the intermediate echoes out of the A-scan are taken as this scalar variable. This method for reconstruction, set up and proven 1981 by the mathematician Floris Takens, is briefly outlined. A feature is extracted out of Recurrence Plots, which are generated out of the representation of the dynamical system (the part under ultrasonic test) in reconstructed state space. This approach is known as Recurrence Quantification Analysis.

First results for correlating a feature out of Recurrence Plots, the determinism DET, with the BWE height are shown. The best correlation was achieved with a parameter setting generally not recommended for RQA and giving a reverse correlation than expected. Future work will elaborate this on samples of other material and with “natural” porosity.

1. Introduction: the Task of Porosity Assessment in CFRP in Special Situations

The standard procedure for the production of parts from Carbon Fibre Reinforced Polymers (CFRP) for Airbus aircrafts is 100% Non-Destructive Testing using ultrasound. In general, this is performed in pulse-echo mode, where one transducer from one side sends an ultrasonic pulse into the part under inspection and receives the returning echoes out of the sample.

The evaluation of porosity in CFRP is done by assessing the back-wall echo (BWE), the echo returned from the back side of the part under inspection. Pores of sizes from a few µm up to several 100 µm (cf. [1] p 57 and [2]) do in general not cause a direct echo that can be evaluated as from a delamination (a material separation), because their size is too small. However, they act as scatterers of sizes approximately equal to and below the wave length and thus reduce the ultrasonic energy: The back-wall echo decreases.

A reduction of the BWE – in comparison to a defect-free area of the same build-up and thickness – of 6 dB, 12 dB or 18 dB, respectively, in dependence of the thickness of the part, is considered as critical and results in an indication out of the inspection (provided that certain dimensions are exceeded). Figure 1 shows an A-scan (amplitude scan) with signals from one CFRP sample of the present investigation in an area without and with (light) porosity, respectively, on the left and right hand side.

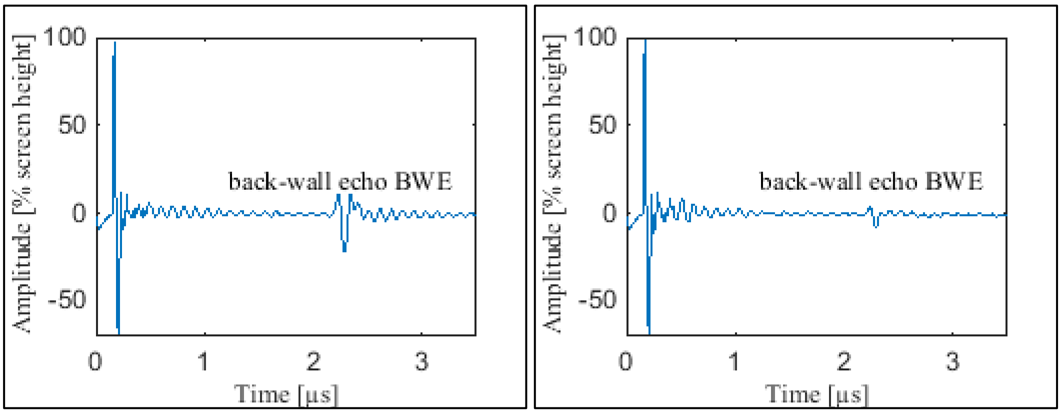

Figure 1: Amplitude scans (A-scans) for a defect free area of a CFRP sample (left hand side) and an area with (light) porosity (right hand side) [time corrected gain used]

However, in several situations no back-wall echo occurs or can be evaluated due to the build-up and geometry of the part. Examples are bonded parts or sandwich parts with CFRP skins and e.g. a honeycomb core. Here, a BWE does not exist or varies due to e.g. a non-homogenous bonding between skin and core of sandwich parts. To this day, no quantitative statement about porosity in CFRP is possible for these situations of ultrasonic testing in production. Parts have to be designed in assuming that there is high porosity present. A method to assess porosity in parts without proper back-wall would allow designs without this limiting assumption and thus provide a weight (and thus, cost) saving potential.

Many approaches in the literature work on the influence of porosity and the attenuation and velocity of signals, thus using the back-wall echo (cf. [3] pp 2291 and an overview in [4]). [5] present an approach, looking at the intermediate echo as in the present paper, based on a "time-frequency, time-energy analysis", to detect "enclosed zones of porosity in otherwise safe parts" in contrast to porosity distributed over the volume. [3] works on an algorithm based on Linear Predictive Coding. This presents an interesting approach from speech processing without the need of a back-wall echo, assuming linear behaviour of the system.

2. The Approach: State Space Reconstruction and Recurrence Quantification Analysis

The reason for the authors' assumption that the proposed state space approach with Recurrence Quantification Analysis (RQA) presents a major step in solution of the current issue is the high complexity and nonlinearity of the ultrasonic wave propagation in the layered anisotropic CFRP with pores. Before explaining this, the background of state space and RQA shall be explicated.

Dynamical systems theory (cf [6]) is the basis and surrounding of state space and RQA. A dynamical system is a technical (or economical, biological…) system that evolves over time. In the present case, the dynamical system under question is the propagation of the ultrasonic wave in the CFRP part under inspection. In general, it can be modelled with the wave equation, containing the 2nd derivative of particle position with respect to time and the 2nd derivative of particle position with respect to position in the part. There are infinitely many variables describing the system (particle displacements and their velocities for each position in the part). All these variables open up the so-called phase space or state space.

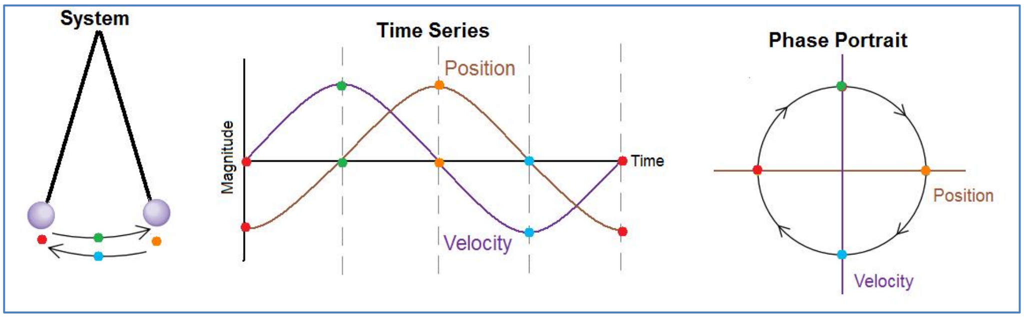

Figure 2: Pendulum as a dynamical system with its representation in state space (here: phase portrait, right hand side) [7]

To give a very simple case for illustration of a dynamical system, an undamped non-driven pendulum in earth's gravity field can be considered as such. The state of this dynamical system is given by merely two variables: The angle (position) and the [angle] velocity, cf Figure 2 right hand side. These two variables make up the whole state space of this system (here a plane). In this example, the state of the pendulum at one instant in time is completely described by these two variables, thus: by one point in state space.

2.1. State Space Reconstruction

Before coming to recurrence and Recurrence Quantification Analysis, and thus to the point what this all is good for when speaking about the present application in NDT, state space reconstruction shall be elucidated.

When performing an ultrasonic pulse-echo inspection, all we can see is the particle displacement (equivalent to pressure) at one limited area at the surface of the part. We see, as it is often the case, just one variable that we can measure, one scalar so-called *time series*. State space reconstruction, introduced with rise of chaos research, was founded mainly with the work of the Dutch mathematician Floris Takens [8], including a mathematical proof of the following: Consider a dynamical system of several or many variables. In reality only a few, often – as in our case – merely one of the variables is measured. The measurements of this variable form the time series (in our case the A-scan with digitised values). It is now possible to *reconstruct* trajectories in a reconstructed state space that are one-to-one to the trajectories of the original state space, i.e. distinct points of the original trajectories map to distinct points of the reconstructed trajectories (cf [9] p 582). The conditions for this to be possible will not be discussed here; they are given in [10] p 208, cf also [11]. It is assumed that the porosity inside the part has a sufficient influence on the ultrasonic wave that it is detectable at the surface.

The procedure of reconstruction, the so-called delay embedding, goes as follows and is best understood in view of Figure 3 for the example of embedding dimension $d = 3$ and the so-called time delay $\tau = 5$ (steps; here, with a digitisation step of 10 ns, this corresponds to 50 ns). A window is slid over the A-scan. The first state variable ξ_1 at time $t = 10\text{ns} = t_1$ is given by the value of the A-scan x_1 at 10ns. The second variable ξ_2 at time t_1 is given by the value of the A-scan $x_6 = x_{1+\tau} = x(t = 60\text{ns})$, the third is given by the value $x_{11} = x_{1+2\tau} = x(t = 110\,\text{ns})$. To derive the first state variable at time $t = 20\text{ns} = t_2$, the value $x_2 = x(t = 20\text{ns})$ is taken. For the second variable ξ_2, the value of the A-scan a time τ later is taken, $x_7 = x(t = 70\,\text{ns})$, and so forth. For a more detailed description, see e.g. [10] pp 205.

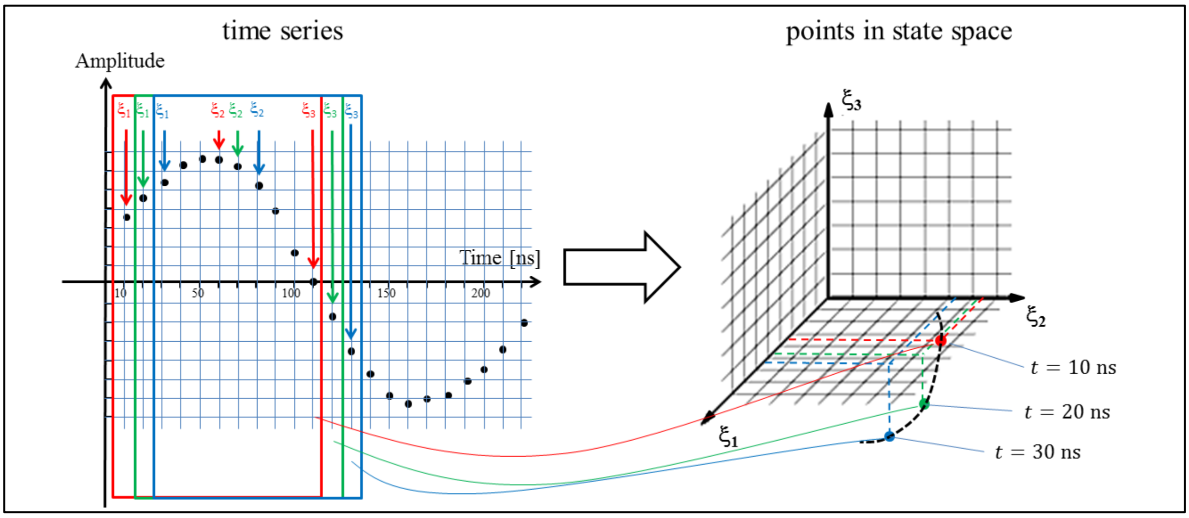

Figure 3: Principle of delay embedding for the example of embedding dimension $d = 3$ and time delay $\tau = 5$

2.2. Recurrence Quantification Analysis

Once the state space has been reconstructed, different features are extracted from the trajectory in state space. These are related to the recurrence of the system's state. Recurrence describes the fact that one state of the system (at one instant in time) is close to another state of the system at another instant in time. A frictionless, not driven pendulum in the gravitational field of the earth returns to its state exactly after one period.

In 1987, [12] introduced the Recurrence Plot RP (being the graphical presentation of the recurrence matrix, cf [13] p 241). The recurrence matrix compares each with every state of the system (in the finite observation time) and contains a "1" (or black dot in the RP) in case the two compared states are recurrent (i.e., near to each other), and gives a "0" (or white dot in the RP) in case they are not.

"Near to each other" has to be defined: First, in mathematical terms, a metric has to be chosen for measuring a distance between points in state space. Second, a threshold ϵ has to be set to calculate the recurrence: For a distance smaller than this threshold, two points are recurrent; for a distance larger, they are not. Two metrics have been chosen for the current work: the L^2 Norm, that is the Euclidean distance; and the angular distance as proposed for RQA by [14] in chapter 3.3.1. The angular distance is independent of scaling of the values of the original time series. This is an advantage in terms of NDT and ultrasonic inspection: Differences in calibration and thus gain and height of the signal will have none or a minor influence on the results of RQA.

Analyses of Recurrence Plots have evolved over the last almost 30 years to Recurrence Quantification Analysis (RQA) [15]. Several features are generated out of the Recurrence Plots (cf. [13] chapter 3.5). In this approach for NDT, the determinism DET is evaluated as feature to present a BWE-equivalent. (Some correlations were also achieved using the Recurrence Rate, which is simply a percentaged summing up of recurrence points, but turned out to be not as powerful as DET.) The minimum line length, having to be at least 2, has to be chosen for determining DET; DET is then the fraction of recurrence points belonging to diagonal lines being equal to or longer than the minimum line length. Diagonal lines exist if a section of the trajectory of the time evolution in state space stays roughly parallel to another section of the trajectory, cf. [13] p 244.

2.3. Why Recurrence Quantification Analysis for NDT?

Non-Destructive Testing involves physical principles that are often nonlinear in their behaviour. In the current case of ultrasonic testing of CFRP, the occurrence of porosity presents a cause for high nonlinearities (besides the anisotropic and layered structure of the material): "nonlinear scattering between different scatterers" is known as (one part of) "multiple scattering" ([16] p 3482). The situation is complex because of the fact that pore sizes are in general smaller, but partly not significantly smaller than the wavelength. A great amount of work has been emphasised on the case of scatterer sizes smaller than 0.03 times the wavelength (see e.g. [17]), whereas in this paper we have the "more difficult case where the ratio of wavelength to scatterer size can be arbitrary" ([18] p 512).

Pre-investigations on the frequency content of the intermediate echoes have revealed that there are not negligible effects in the frequency range above the dominating 5 MHz frequency depending on whether or not porosity is present; however, these effects could not properly be correlated with the back-wall echo. They support the assumption that porosity has significant nonlinear influence on the ultrasonic wave propagation. This is why the authors assume that RQA as a tool appropriate for and even relying on nonlinear system behaviour is a convenient means for delivering a BWE-equivalent for the presented task.

[19] also propose to use RQA, in their case for the assessment of porosity in cement pastes, using ultrasonic testing, too. They use Recurrence Plots to investigate the degree of predictability in the signals, ultrasonic scattered signals being a combination of deterministic and stochastic signals ([19] p 1905).

3. Measurements

For the ultrasonic measurements, a commercial lab system from M2M with an Olympus phased array probe was used. Three CFRP samples, designated CG070M13/14/15, with artificially introduced fields of different amounts of porosity were inspected. The samples were all from the same fabric material and all of around 7 mm thickness. These samples were manually scanned, creating a volume scan using the phased array technology. Such a scan covered around half of each sample and consisted of around 30 times 65 measurement points and thus A-scans. Figures in this paper are based on a scan of sample CG070M15 with the highest porosity; the correlation for three scans of each of the samples have also been checked.

The probe has a peak frequency of 5 MHz and is driven as such. The data (recorded with sampling rate of 100 MHz) was opened and saved with the Ultis software package. Then, it was loaded into Matlab®, in which all signal processing was performed using self-programmed functions.

4. Evaluation and Results

With varied parameters recurrence matrices are determined for the intermediate echoes out of each A-scan – each time series – of one ultrasonic volume scan. Out of each recurrence matrix, the determinism DET is calculated. DET is then tested as a BWE-equivalent by plotting it as a C-scan against the BWE C-scan. The parameters that deliver the best BWE-equivalent have been chosen. The embedding parameters time delay τ and embedding dimension d, and the recurrence threshold ε and in addition the value for the minimum line length for DET have been varied for two distances, Euclidean distance and angular distance.

The angular distance appeared to be more robust than the Euclidean one in the sense that the correlation between DET and BWE is less dependent of change of the embedding parameters and it stayed similar over a large variation of the threshold ε. This is assumed to be related to the independence of scaling of points in state space. With this independence, points in the same section of state space are considered as recurrent even if they originate from different depths of the part and have thus different heights.

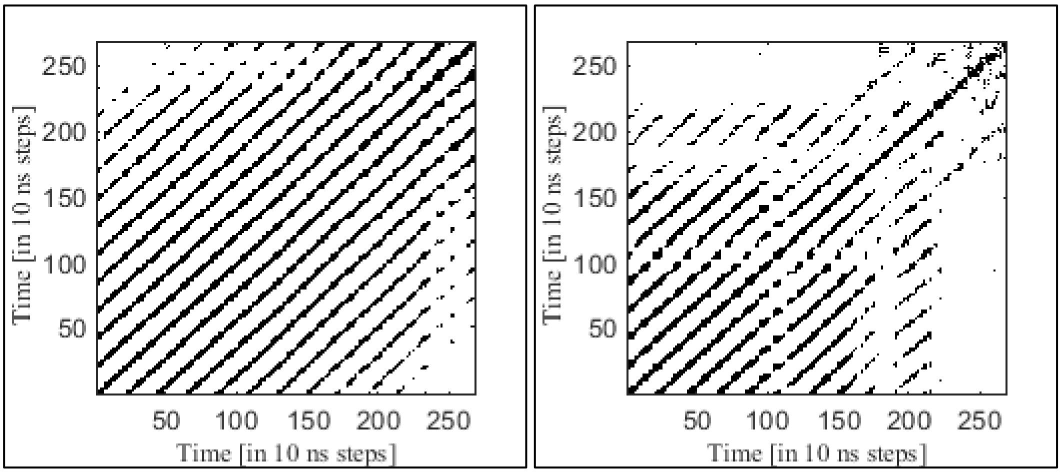

Figure 4: Recurrence plot ($\varepsilon = \pi/4$) of A-scans embedded into reconstructed state space with $d = 5$ and $\tau = 8$, angular distance used, for porosity free area (left hand side) and an area with porosity (right hand side)

Figure 4 shows Recurrence Plots of the intermediate echoes of one A-scan out of an area without and with porosity, respectively, on the left and right hand side. The diagonal lines, which are typical for periodic systems, are rather thick. It is difficult with the given data to obtain any recurrence without including subsequent and preceding data points in time. Nevertheless, the downfall of recurrence with the presence of porosity can be clearly seen in Figure 4; a fairly good correlation between DET and BWE can be achieved. Figure 5 left hand side represents a BWE C-scan of one scan of sample CG070M15 including the area of largest porosity. A C-scan of DET as BWE-equivalent is shown in Figure 5 right hand side.

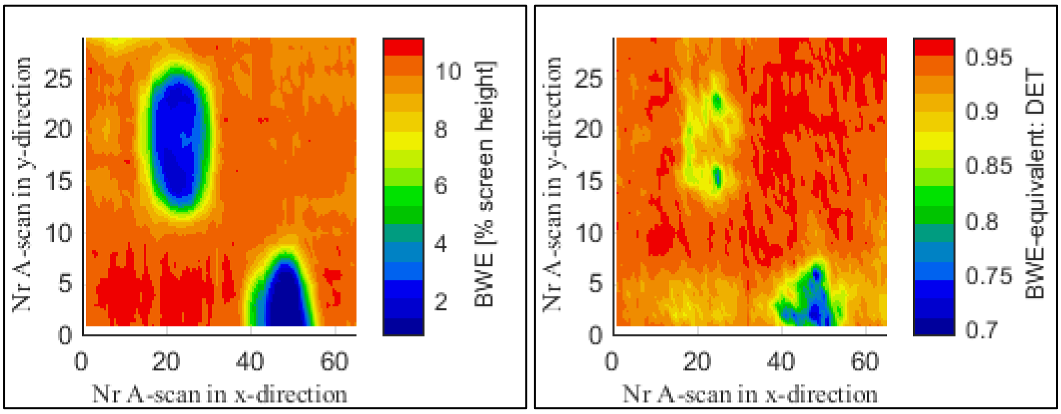

Figure 5: C-scan of back-wall echo BWE (left hand side) and back-wall echo equivalent (right hand side), the latter being the feature DET out of recurrence plots for every A-scan for parameters $d = 5$, $\tau = 8$, $\varepsilon = \pi/4$, angular distance, and minimum line length of 4

It shall be mentioned that an even better result could be achieved with the Euclidean distance, however, with parameters leading to significantly higher recurrences than any guidelines of RQA recommend, cf [15] chapter 1.2.1. The correspondent recurrence plots are shown in Figure 6 (same A-scans used as in Figure 4).

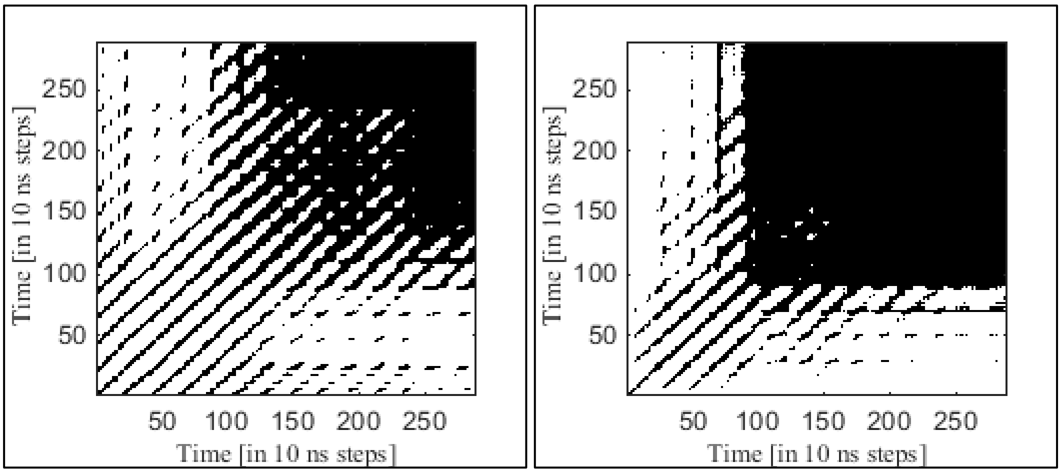

Figure 6: Recurrence plot ($\varepsilon = 2$ [% screen height]) of an A-scan embedded into reconstructed state space with $d = 3$ and $\tau = 6$, Euclidean distance used, for porosity free area (left hand side) and an area with porosity (right hand side)

The related C-scans are given in Figure 7. The correlation here is *reverse* to the one shown before for the angular distance (note that the colour scale for the right C-scan is reversed): The lower the BWE (and thus higher the porosity), the *higher* DET is. Nevertheless, this correlation appeared to be robust in the sense that scans of the two other samples had similarly good correlations. This effect will be further elaborated, especially on samples of other material and with "natural" porosity, in future work.

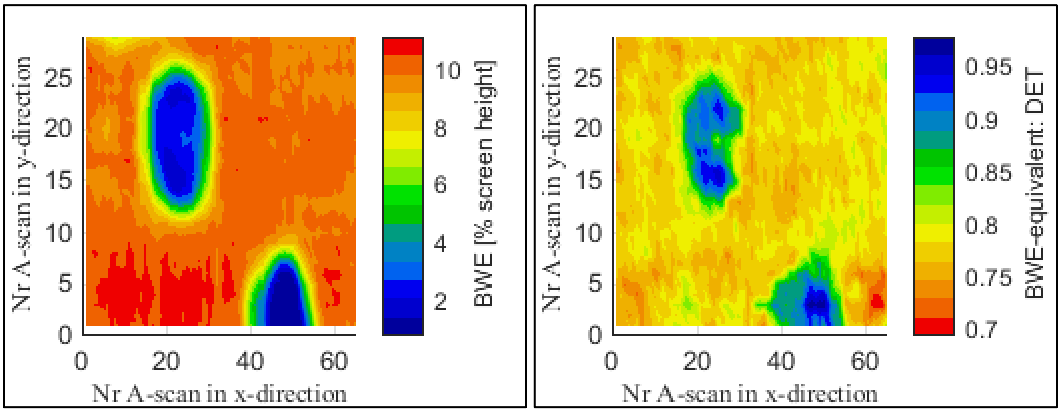

Figure 7: C-scan of back-wall echo BWE (left hand side) and back-wall echo equivalent (right hand side), the latter being the feature DET out of recurrence plots for every A-scan for parameters $d = 3$, $\tau = 6$, $\varepsilon = 2$ [% screen height], Euclidean distance, and minimum line length of 10

5. Summary

Recurrence Quantification Analysis (RQA) is proposed for the first time for evaluation of ultrasonic testing of porosity in CFRP. First results on fabric CFRP samples with artificially introduced porosity are shown. The determinism DET out of Recurrence Plots (RPs), generated on basis of the intermediate echoes, is shown as back-wall echo equivalent against the back-wall echo. The angular distance for calculation of RPs and DET leads to fairly good correlations; the Euclidean distance leads to even better correlations, however, with parameter settings not recommended for RQA in general and with a *reverse* correlation. Future work will elaborate this and test the robustness of the procedure on samples of other materials and with "natural" porosity.

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