Recurrence Quantification Analysis for Non-Destructive Evaluation with an Application in Aeronautic Industry

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Abstract. This paper considers work performed so far on utilising Recurrence Quantification Analysis as a Non-Destructive Evaluation tool to assess porosity in Carbon Fibre Reinforced Polymers (CFRP) via ultrasonic testing. Recurrence Quantification Analysis (RQA) has been developed over the last almost 30 years for varied areas such as climate research, medical research or engineering. It is based on the theory of dynamical systems, systems that evolve over time, and considers their recurrences, i.e. the situation in which a state of the system is similar to a state it possessed earlier in time.

For the standard ultrasonic pulse-echo inspection of structural CFRP parts for Airbus aircrafts, porosity is assessed via the so-called back-wall echo (BWE), i.e. the echo returning from the back side of the sample. However, in situations with complex geometry like skin-stringer structures or sandwich parts, this BWE does not exist or cannot be properly evaluated. The aim is to get a BWE equivalent out of the intermediate echoes that start after the surface echo and end before the BWE.

Whereas successful investigations to create a BWE equivalent using RQA are in detail explained in two former publications, this paper emphasises
• the motivation to assess porosity in structural CFRP parts in aeronautic industry,
• the effects observed with Recurrence Quantification Analysis. These effects are strongly related to the layered structure of the CFRP in the investigations performed so far.

Future work will include other materials and natural porosity.

1 Introduction

This paper considers earlier work on utilising Recurrence Quantification Analysis as a Non-Destructive Evaluation tool to assess porosity in Carbon Fibre Reinforced Polymers via ultrasonic testing, (to be) published in [1, 2]. Section 2 emphasises on the motivation for the work for aeronautic industry, the method of Recurrence Quantification Analysis is briefly explained in section 3, and details on the physical background of the effects observed are given in section 4 before concluding with section 5.
2 Motivation: Porosity Assessment in Carbon Fibre Reinforced Polymers in Aeronautic Industry

The usage of Carbon Fibre Reinforced Polymers (CFRP) for Airbus aeroplanes went up from 25% for the A380 to 53% for the A350XWB. CFRP is a composite material built up from layers consisting of carbon fibres, which are either pre-impregnated with resin or filled with resin after the laying process and then cured under heat and temperature in an autoclave. CFRP leads with its high ratio between mechanical strength and weight to less fuel consumption and thus cost.

Defects occurring during CFRP manufacture can have a significant influence on the mechanical strength of the part. These influences can be summarised in knock-down factors, which represent the ratio between the critical load (causing a failure of the structure) for the structure containing a defect and the critical load for an ideal, defect-free structure. Porosity has a decreasing effect for example on Interlaminar Shear Strength [3, 4]. Therefore 100% Non-Destructive Testing is performed for structural parts from CFRP for Airbus aeroplanes after manufacturing. This is generally carried out using ultrasonic testing in pulse-echo mode, i.e. with one transducer from one side. This transducer sends an ultrasonic pulse into the part. The ultrasound is partly reflected and partly transmitted at interfaces between different materials. Thus, the transducer receives reflections from the inner of the CFRP part and of its opposite side (“back-wall”). These echoes can be displayed in a so-called A-scan. Defects as delaminations (internal material separations) represent an additional echo, which can be clearly identified and evaluated in the A-scan (Figure 1).

Porosity does not create echoes that can directly be evaluated in an A-scan. However, the many rather small pores (with sizes mostly significantly smaller than the wave length and seldom up to approximately equal to the wave length) reflect small portions of the ultrasonic wave in direction to the transducer and in other directions. Thus less ultrasonic energy reaches the back-wall and the so-called back-wall echo decreases: the back-wall echo is a measure for the content of porosity in CFRP. For CFRP parts for Airbus aeroplanes, a back-wall echo reduction of 6 dB, 12 dB and 18 dB, respectively (depending on thickness of the part) is the relevant evaluation threshold.
2.1 Obstacles to Detect Porosity Today

Several situations exist for which the above described way of evaluation cannot be gone. Either there is no back-wall and thus back-wall echo at all, or there are other influences on the back-wall echo that cannot be distinguished from the influence of potential porosity on this echo.

Prior to listing these situations, the co-bonding process, cf [2], is briefly described, because it plays an important role in the obstacles to detect porosity. It involves one precured part. The bonding of this part and the curing of the non-cured bonding partner is done in the same curing cycle.

A main example for not having a back-wall echo is
• co-bonded stringers. Stringers, stiffening elements of the fuselage in flight direction, are joined to the fuselage skin using the co-bonding process. Accordingly, the fuselage skin, which has not been cured before, is only available for ultrasonic testing with stringers attached. In the areas of the stringer web, no back-wall echo can be obtained (Figure 2).

![Figure 2: Sketch of skin-stringer structure without back-wall echo in the area of the stringer web](image)

Additional influences on the back-wall echo that do not allow its evaluation are
• geometric effects in non-plane parallel parts. If the surface of the part (on which the ultrasonic wave enters it) and the opposite side, the back-wall, are not parallel to each other, the sound from the back-wall is reflected in other directions than directly to the transducer. The ultrasonic probe only receives smaller portions of the wave; the back-wall echo decreases. Especially if the angle between surface and back-wall varies as for spherically shaped parts, the height of the back-wall echo changes with the varying angle. In such situations it is difficult to determine whether the observed changes in the back-wall echo are merely due to these geometrical reasons or whether there is an additional reduction caused by porosity. The back-wall echo height fails to be a reliable measure of porosity.
• In CFRP skins of sandwich structures (a core, eg honeycomb, covered with CFRP laminates on both sides, cf [5]), the bonding interface between the laminate and the core may result in echoes varying from location to location, depending on eg a varying amount of adhesive. Again, one cannot tell whether the observed varying “back-wall echo” is only due to this part inherent variations or whether the variations are due to porosity in the laminate.
2.2 Benefits from Detecting Porosity in Situations without Back-Wall Echo

For all cases described above a quantitative statement about porosity, if the back-wall echo does not exist or is unreliable, will be beneficial. Today, in the above described areas, in which no quantitative statement about porosity is possible, the presence of porosity has to be assumed and knock-down factors have to be applied when designing the aeroplane. A method delivering a quantitative statement would allow for better, i.e. more lightweight designs.

A potential evaluation method to overcome the described problems would have to use the information that is available: the so-called intermediate echoes between the surface and the back-wall echo, out of the inner of the material. The aim is to generate a back-wall echo equivalent (BWE equivalent) out of these intermediate echoes. Such a method may be beneficial in further respects.

- Based on the evaluation of intermediate echoes, it may also allow distinguishing between porosity and for example delaminations. The latter cause a back-wall echo reduction (or extinction), too. In the normal evaluation procedure, porosity and delaminations may thus be difficult to distinguish. The existence of a delamination has generally been excluded by looking for direct intermediate echoes beforehand. However, when thinking eg at automatic evaluation algorithms in the future, an (additional) mean of distinguishing indications of delaminations from those of porosity would be beneficial.

- Furthermore, a method based on intermediate echoes might allow statements on the severity of porosity. Once an indication appears, it is beneficial for its assessment to know its criticality. There are limits in this respect when looking at the back-wall echo: A reduction of more than 18 dB (equalling one eights of the original signal) is often difficult to evaluate, because the back-wall echo might be as small as the internal echoes out of the laminate. It may not be possible to make a statement whether the reduction is for example 20 or 30 dB. If an evaluation method enabled such statements from the assessment of the intermediate echoes, this would provide useful information regarding the decision how to proceed with a part in production in which such an indication occurs.

To provide these benefits, Recurrence Quantification Analysis has been proposed as a tool to evaluate the intermediate echoes out of ultrasonic pulse-echo testing with regards to porosity.

3 Method: Recurrence Quantification Analysis

In this chapter, the very basics of Recurrence Quantification Analysis and the underlying Dynamical Systems shall be outlined. For a more detailed account, see [1, 2] and the references mentioned therein.

3.1 Dynamical Systems

Dynamical Systems are systems that evolve over time. They can be represented in a so-called state space (or phase space), the dimension of it being similar to the number of variables describing the system (eg angle and angle velocity for a pendulum). The state of the system at one instant in time is completely described by one point in state space.

One important goal of the theory of dynamical systems is to give qualitative answers on how a system evolves, meaning delivering qualitative solutions of differential equations describing the systems. Whereas basic mathematical lectures cover analytical
solutions of differential equations (for example the one modelling a damped harmonic oscillation), many (nonlinear) differential equations cannot be solved analytically. Especially for so-called chaotic systems, even numerical solutions are impossible. For such systems, very small, not measurable differences in initial conditions and/or in system’s parameters lead to completely different solutions after a short period of time. Chaotic behaviour was recognised by the scientific community in the 70s and 80s of last century. One of the facts discovered was, though long-term prediction is impossible, several statements can be done for chaotic systems. One example is the fact that the states of a chaotic system only possess a limited region in state space.

With the rise of scientific work for chaotic systems, Recurrence Plots were introduced.

3.2 Recurrence Quantification Analysis

An important notion within the theory of dynamical systems is recurrence. This is the situation in which the state of a dynamical system comes near to a state that it possessed earlier in time, for example a pendulum returning to the same position with the same direction of movement.

In 1987, the idea of Recurrence Plots was introduced as a tool representing a complex, high-dimensional dynamical system in a two-dimensional plot [6]. With such a tool the occurrence, number, order etc. of recurrences can be assessed. In the past decades, it developed to a quantifying scientific method, the Recurrence Quantification Analysis (RQA), with applications in many areas such as climate research, medical research or engineering [7]. One of the features determined within RQA to make a statement about recurrences is the so-called determinism [8].

3.3 Delay Embedding

In experimental or engineering situations, most often only a few or just one variable(s) of a process can be measured; not all state variables of the dynamical system are determined. In this respect, the delay embedding [9, 10, 11] gave a significant impulse to investigate experiments with regard to dynamical systems and chaotic behaviour. It allows to reconstruct a (one-to-one mapping of) a dynamical system from a single (scalar) variable. For further information and the detailed procedure, refer to [1, 2] and the references mentioned therein.

4 Application: What Are the Effects of Porosity on Ultrasonic Wave Propagation in CFRP

The use of Recurrence Quantification Analysis has been proposed for evaluation of ultrasonic testing for porosity in cement pastes in [12], later updated with the suggestion to use angular distance in [13] (which allows for an evaluation independent of amplitude effects). The authors conclude that “determinism is strongly related to the degree of ultrasonic scattering”. They measured lower values of the RQA feature determinism (cf. section 3.3) with higher porosity.

The present application aims at the detection of porosity in Carbon Fibre Reinforced Polymers (CFRP) in aeronautic industry for reasons explained in section 2. CFRP as a composite material exhibits numerous interfaces between carbon fibres and epoxy resin, which cause internal reflections and lead to high attenuation of ultrasound, being thus inherent in the material. The more severe reflections appear at the interfaces between different layers (plies), from which the material has been built up. At the edges – the former
surfaces of the single layers – an accumulation of resin exists, which causes significant reflections of the ultrasound in the finally cured part.

Such reflections between the interfaces of the CFRP plies can be best observed if the ply thickness is approximately half the wavelength of the ultrasound. This has been the case for the work performed up to now for RQA on CFRP samples with artificial porosity [1, 2]. These samples of the material 913C-926-35%F have a ply thickness of \( t = 0.35 \text{mm} \). The wavelength \( \lambda \) of the ultrasonic pulse transmitted into the material equals with a mean pulse frequency of \( f = 5 \text{MHz} \) and an ultrasound velocity \( c \approx 3000 \text{m/s} \) according to

\[
c = \lambda f
\]

\( \lambda \approx 0.6 \text{mm} \approx 2t \). With such a ratio, the intermediate echoes from the inner of the CFRP form a rather regular sine wave (Figure 3 right hand side).

\[
\lambda = \frac{c}{2f}
\]

This is an effect due to summing up of the reflections of the ultrasonic pulse at the subsequent interfaces. It is assumed that this is intensified by effects of constructive interference of parts of the wave train (Figure 4 bottom). Such interference effects are known for example at one or more thin films in optics; these are however usually considered with a non-perpendicular incidence wave, see eg [14].
If now pores occur inside the material, they lead to (small) reflections additional to the ones of the layered material. These reflections may, due to the often sphere-like nature of the pores, go into any direction: back to the transducer or in any other direction. Looking at the entire ultrasonic wave propagation in the sample as one dynamical system, this is thus changed by the presence of pores. The question is how the portion of the ultrasonic wave that travels back to the transducer is affected. Looking at this from the viewpoint of delay embedding, the question is whether the whole ultrasonic wave propagation (or relevant portions of it) can be reconstructed from the time series that “the transducer sees”. Practically, in the current application it has to be asked whether a significant difference can be seen between the situation without and with porosity.

Different effects of porosity are possible when considering the A-scan received by the transducer:

- Signal amplitudes change; either they decrease because of pore echoes not going back to the transducer, or they increase because of pore echoes travelling back to the transducer;
- The additional pore echoes disturb the rather periodic signal, the periodicity of the intermediate echoes decreases; more stochasticity occurs.

Both items were hypothesised in [2]. For the situation investigated there – one material type and artificially introduced porosity – both hypotheses were corroborated. It was shown that the A-scan received by an ultrasonic transducer in pulse-echo inspection exhibits significant differences when porosity occurs, which were observed via a
reconstruction of (relevant portions) of the underlying dynamical system (the ultrasonic wave propagation in the part). The RQA feature determinism proved to present an appropriate back-wall echo equivalent.

## 5 Conclusion and Outlook

The current paper considers earlier work on utilising Recurrence Quantification Analysis to assess porosity in Carbon Fibre Reinforced Polymers [1, 2]. It emphasises on the motivation of the work, describing the impact of porosity on structural CFRP parts in aeronautic industry and elaborating the advantages of making statements about porosity in situations in which this is not possible today. Furthermore, the effects seen in earlier work are further detailed and elaborated as a deviation from the periodic intermediate echoes achieved for the investigated samples due to a ratio between wavelength of the ultrasonic pulse and ply thickness of approximately 2.

Further work has to substantiate the results, which have been achieved so far on one material type with artificial porosity in ultrasonic pulse-echo technique. Tests with other materials and natural porosity are planned.

## 6 References