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COMPOSITES THEORY AND PRACTICE

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INFLUENCE OF DEFECT DIAMETER ON ITS DETECTION IN MILLING PROCESS OF COMPOSITE MATERIAL USING RECURRENCE PLOT TECHNIQUE

This paper presents the study of the detection of "artificial" defects by nonlinear techniques based on the cutting forces recorded during milling process of composite material. The "artificial" defects are intentionally drilled holes of different diameters made in carbon fiber reinforced plastics. The cutting force was analyzed by recurrence plots and recurrence quantifications analysis. The main purpose of this work is to determine the size of an artificial defect that is possible to detect as well as select the recurrence quantifications for damage detection.

Keywords: **detection of defects, recurrence plots, recurrence quantification, milling, composite**

WPŁYW ŚREDNICY DEFEKTU NA WYKRYWALNOŚĆ W PROCESIE FREZOWANIA MATERIAŁU KOMPOZYTOWEGO Z WYKORZYSTANIEM TECHNIK REKURENCYJNYCH

Przedstawiono badania wykrywalności wad „sztucznych” za pomocą nieliniowych technik na podstawie przebiegów sił skrawania zarejestrowanych podczas frezowania materiału kompozytowego. Wadami „sztucznymi” są celowo wywiercone otwory o różnych średnicach w polimerowym materiale kompozytowym wzmocnionym włóknem węglowym. Przebiegi sił poddano analizie za pomocą metody wykresów oraz wskaźników rekurencyjnych. Głównym celem pracy jest ustalenie wielkości sztucznej wady możliwej do wykrycia oraz wyselekcjonowanie wskaźników rekurencyjnych służących do jej detekcji.

Słowa kluczowe: **detekcja wad, wykresy rekurencyjne, wskaźniki rekurencyjne, frezowanie, kompozyt**

INTRODUCTION

Recurrence plots and recurrence quantification analysis are special methods designed for nonlinear time series. The recurrence plot method is based on a special plot (diagram) which consists of white and dark points. In the literature several methods dedicated to detecting different damages/defects in machinery and equipment can be found (for example vibration frequencies [1, 2] are used to study damaged and undamaged aluminum plates). The dynamics of a machine element with a hidden defect differ from the dynamics of an undamaged element [3]. By comparing the vibration frequencies, it is possible to detect damage [4]. Recurrence quantification is calculated at the time of the appearance of additional peaks in the recorded frequency, which is the symptom of a crack. Among the many defects, there is also intercrystalline corrosion [5], which can be detected by the electrochemical analysis of current noise signals and the recurrence plot. The non-invasive technique consisting of passing a current through a sample gives results showing intercrystalline corrosion as evidenced by the change in the amplitude of the current noise.

The paper presents analysis of the size of damage on its detection based on signals in the form of cutting forces generated in the milling process of the composite. For this purpose, the advanced method dedicated to nonlinear time series has been used.

RECURRENCE PLOT AND RECURRENCE QUANTIFICATION METHODOLOGY

Recurrence plots

The recurrence plot is a method for nonlinear time series analysis introduced in 1987 by Eckman [6]. The plot is used to illustrate the recurrence of the phenomenon. From the mathematical point of view, the recurrence plot can be described by the simple formula:

$$R_{i,j} = H\left(\varepsilon - \left\| x_i - x_j \right\|\right) \quad (1)$$

where i, j denote state numbers in space and have values 1,2 ..., N, where N denotes the number of points to be analyzed, H is the Heaviside function, ε is a predefined threshold distance, $\|x\|$ is the Euclidean norm of vector x in the phase space.

From the graphical point of view, RP is a square matrix of NxN, which contains points i, j.

The first stage in creating a recurrence plot is to reconstruct delay vector X (Equation (2)) from the original recorded signal by the delay method [7].

$$X = (x_i, x_{i+d}, x_{i+2d}, ..., x_{i+(m-1)d}), \quad (2)$$

where x is the analyzed time value, d is the time delay, m is the embedding dimension.

Time delay d is usually chosen using the Average Mutual Information (AMI) method [8]. Embedding dimension m is determined by the False Nearest Neighbors (FNN) method [9]. Parameter ε (called the threshold) is the number of points analyzed in the recurrence structure [10]. The value of the threshold usually should be 10÷20% of the amplitude of the analyzed signal (for example cutting force) [11]. Other methods and suggestions for selecting the threshold can be found in the literature. The authors of paper [12] show that parameter ε represents 1% of the recursion. The literature also proposes five times the standard deviation [13] or the corresponding analytical formulas [14]. Paper [10] proposes using the surrogate technique introduced by Theil [15] as a supplement to the statistical method. By comparing nonlinear and surrogate sets, one can distinguish whether the observed data can be sufficiently described in a linear process. If the estimated properties of the original data are close to the replacement properties, then the observed data does not have any nonlinear properties.

Recurrence quantification analysis

Because of the difficulties in interpreting and analyzing recurrence plots, special parameters called recurrence quantifications (RQA) were introduced [16-19]. Generally, RQA are statistical descriptions of the RP structure. The common quantifications are:
- recurrence rate RR - percentage of recurrence points (black dots) related to all points in the plot,
- determinism DET - percentage of recurrence points that form parallel diagonal lines on the recurrence plot,
- averaged diagonal length L occurring in the recurrence plot parallel to the main diagonal line,
- length of the longest diagonal line L_{max} occurring in the recurrence plot parallel to the main diagonal,
- trapping time TT is the length of the average horizontal line on the recurrence plot,
- length of the longest vertical line on the recurrence plot,
- laminarity characterizing the percentage of points forming horizontal lines in relation to all the points in the RP structure,
- entropy ENTR is the probability of the length of linear segments parallel to the main diagonal of the recurrence plot,
- clustering coefficient CC is a quantification that shows the probability that two neighbors in each state are also neighbors,
- recurrence time of the 1 st and 2 nd type (T1, T2),
- transitivity TRANS,
- recurrence period density entropy RPDE.

RESULTS AND ANALYSIS OF EXPERIMENTAL STUDY

The machining of carbon fiber reinforced plastic was conducted on a vertical machining center Avila-VMC800HS. The cutting forces were measured using a 3D Kistler dynamometer (type 9257B) which is connected to a multichannel charge amplifier (type 5070). The measured signals were recorded by Dynowave software (type 2825A) with Dynoware (type 5697A). The sampling frequency was 0.0002 s with the accuracy of 0.00001 N for the devices which were used in the study.

The dedicated milling cutter diameters d_f = 20 mm consisting of double-coated diamond inserts (PCD) with the symbol EC1004FR-PCD KD 1410 were used for the tests. Figure 1 shows the experimental set-up.

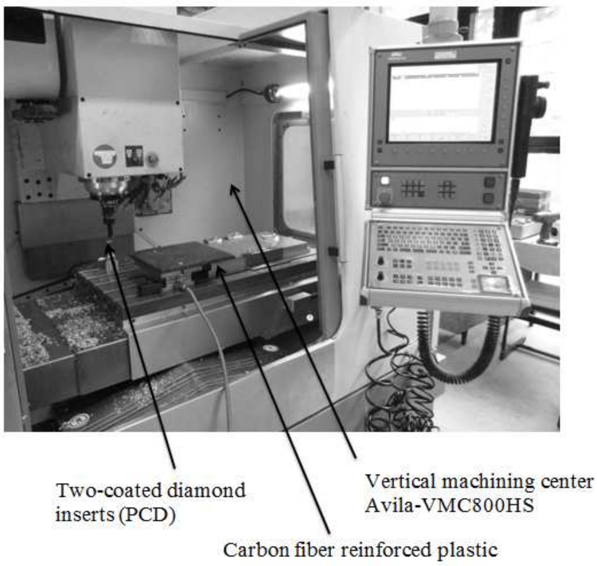

Fig. 1. Scheme of test stand

Rys. 1. Schemat stanowiska badawczego

During machining, the influence of the artificial defect diameter on the detection by means of the RP and the RQA methods at a constant feed rate, cutting speed and depth of cut was investigated. The feed rate was v_f = 2 mm/edge and cutting speed v_c = 250 m/min.

Table 1 shows all the parameters used in the study experiment. The variable for the study was the diameter of the hole (damage) $\phi\ d_o$: ϕ 2 mm, ϕ 4 mm and ϕ 6 mm. The research was done at the constant cutting depth a_p = 2 mm (Fig. 2).

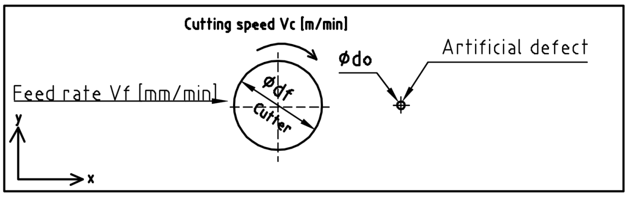

Fig. 2. Scheme of milling process with artificial defect (hole) $\phi\ d_o$

Rys. 2. Schemat obróbki frezowaniem ze sztuczną wadą w postaci otworu $\phi\ d_o$

TABLE 1. **List of parameters used in experiment**
TABELA 1. **Zestawienie parametrów użytych w badaniach**

	ϕ d_o [mm]	***ap* [mm]**	**v_f [mm/blade]**	**v_c [m/min]**
1	2	2	0.2	250
2	4	2	0.2	250
3	6	2	0.2	250

The cutting force tests with the damage (hole) were compared with the same tests without artificial defects.

INFLUENCE OF HOLE DIAMETER

Figure 3 shows an example of cutting force *Fx* obtained by face milling of a flat surface. The defect was present in the form of a hole of diameters of about ϕ 2 mm, ϕ 4 mm and ϕ 6 mm.

The first step to creating a recurrence plot is to determine the time delay *d* parameter using the Mutual Information Method. Next, embedding dimension *m* was selected using the Nearest Neighbor Method. For example, for the cutting force with the hole diameter of ϕ 2 mm, time delay d = 8 and embedding dimension m = 5. Threshold ε has been taken as 20 N.

The next step is to create the recurrence diagram based on Equation (1), and the results are presented in Figure 4. For this purpose, the CRQA software that is an add-on to Matlab was used [20]. For machining of the polymer composites with the artificial defect diameter of ϕ 2 mm 1000 points were taken for analysis (Fig. 4a), for the damage ϕ 4 mm 2000 points (Fig. 4b) and for ϕ 6 mm 3000 points (Fig. 4c). The RP diagram for a "healthy" milling process in (Fig. 4d) is shown. A hole in the form of a "cross" can be observed in the obtained recurrence plots.

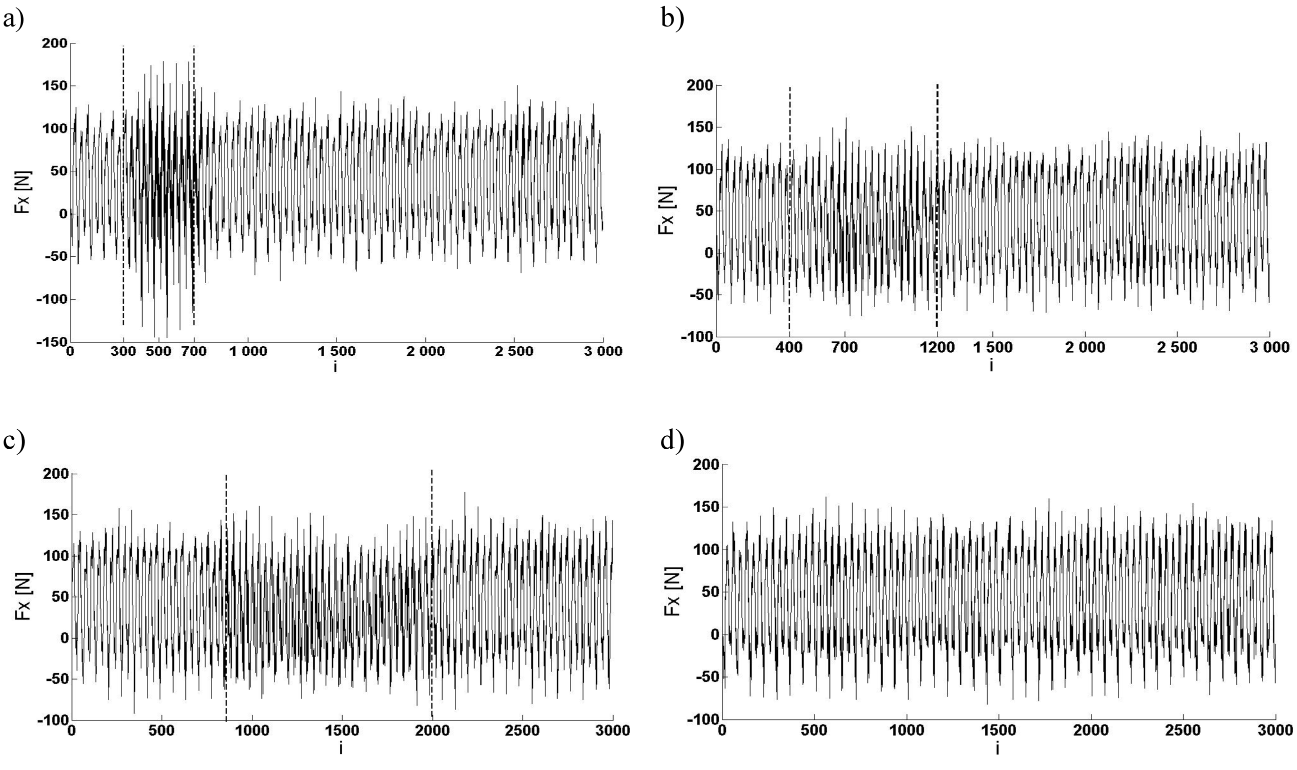

Fig. 3. Cutting forces *Fx* obtained by milling flat surface: a) with hole diameter ϕ 2 mm, b) with hole diameter ϕ 4 mm, b) with hole diameter ϕ 6 mm, d) without hole

Rys. 3. Przebieg siły *Fx* uzyskany w wyniku frezowania płaskiej powierzchni: a) z otworem o średnicy ϕ 2 mm, b) z otworem o średnicy ϕ 4 mm, c) z otworem o średnicy ϕ 6 mm, d) bez otworu

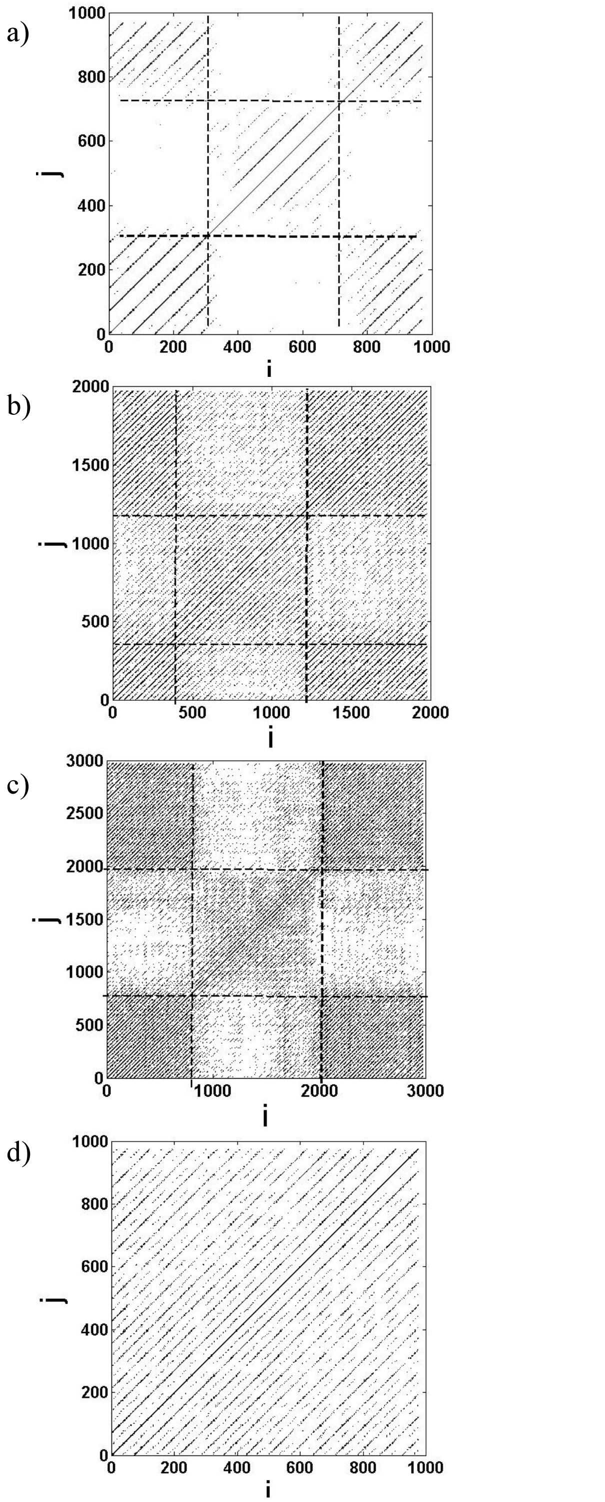

Fig. 4. Recurrence plots obtained from cutting force signals: a) with hole diameter ϕ 2 mm (m = 5, d = 8, ε = 20), b) with hole diameter ϕ 4 mm (m = 4, d = 9, ε = 20), c) with hole diameter ϕ 6 mm (m = 4, d = 9, ε = 20), d) without hole (m = 4, d = 8, ε = 20)

Rys. 4. Wykresy rekurencyjne uzyskane z sygnałów pomiarowych sił skrawania: a) z otworem o średnicy ϕ 2 mm (m = 5, d = 8, ε = 20), b) z otworem o średnicy ϕ 4 mm (m = 4, d = 9, ε = 20), c) z otworem o średnicy ϕ 6 mm (m = 4, d = 9, ε = 20), d) bez otworu (m = 4, d = 8, ε = 20)

The RQA were calculated in order to locate defects in the cutting time series. For this purpose, the so-called: *"moving window method"* is applied. This technique is based on moving the adopted range (window) of points (in this article the size of 200 points was assumed).

The analysis based on a constant *RR* quantification parameter (the same number of points were analyzed in all the tests).

Figure 5 shows determinism (*DET*). The position of the hole is indicated by the vertical dashed lines.

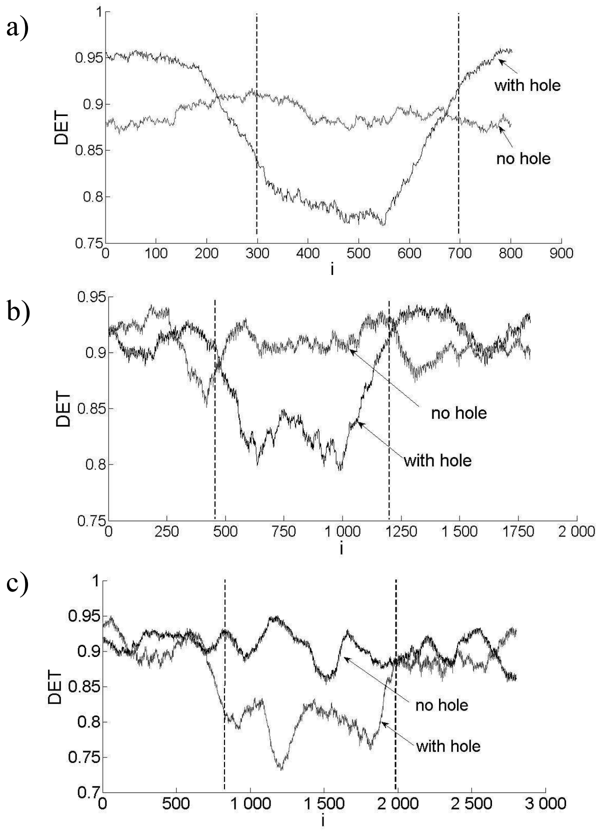

Fig. 5. Determinism DET of recurrence plot obtained by milling a flat surface: a) with hole diameter ϕ 2 mm (m = 5, d = 8, ε = 20) and without hole (m = 4, d = 8, ε = 20), b) with hole diameter ϕ 4 mm (m = 4, d = 9, ε = 20) and without hole (m = 4, d = 9, ε = 20), c) with hole diameter ϕ 6 mm (m = 4, d = 9, ε = 20) and without hole (m = 4, d = 9, ε = 20)

Rys. 5. Determinizm DET dla wykresu rekurencyjnego uzyskanego w wyniku frezowania płaskiej powierzchni: a) z otworem o średnicy ϕ 2 mm (m = 5, d = 8, ε = 20) i bez otworu (m = 4, d = 8, ε = 20), b) z otworem o średnicy ϕ 4 mm (m = 4, d = 9, ε = 20) i bez otworu (m = 4, d = 9, ε = 20), c) z otworem o średnicy ϕ 6 mm (m = 4, d = 9, ε = 20) i bez otworu (m = 4, d = 9, ε = 20)

The next plots show the quantifications that can detect defects, *CC* (Fig. 6), *LAM* (Fig. 7). Among the all quantifications, some of them are unable to detect the defects. For example, length of the longest diagonal line L_{max} (Fig. 8) cannot be used as a damage detector.

The presented quantifications refer to holes with diameters of ϕ 2 mm, ϕ 4 mm and ϕ 6 mm where some changes in the RQA plots are observed. For the holes ϕ 2 mm, there are changes in the interval of points from 300 to 700, for ϕ 4 mm in the interval of 400 to 1200, and for ϕ 6 mm in the points from 800 to 2000.

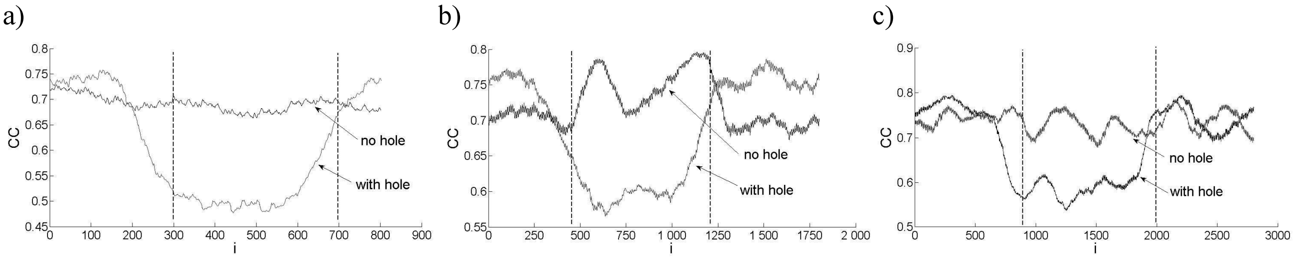

Fig. 6. Clustering Coefficient CC of recurrence plot: a) with hole diameter ϕ 2 mm (m = 5, d = 8, ε = 20) and without hole (m = 4, d = 8, ε = 20), b) with hole diameter ϕ 4 mm (m = 4, d = 9, ε = 20) and without hole (m = 4, d = 9, ε = 20), c) with hole diameter ϕ 6 mm (m = 4, d = 9, ε = 20) and without hole (m = 4, d = 9, ε = 20)

Rys. 6. Clustering Coefficient CC dla wykresu rekurencyjnego: a) z otworem o średnicy ϕ 2 mm (m = 5, d = 8, ε = 20) i bez otworu (m = 4, d = 8, ε = 20), b) z otworem o średnicy ϕ 4 mm (m = 4, d = 9, ε = 20) i bez otworu (m = 4, d = 9, ε = 20), c) z otworem o średnicy ϕ 6 mm (m = 4, d = 9, ε = 20) i bez otworu (m = 4, d = 9, ε = 20)

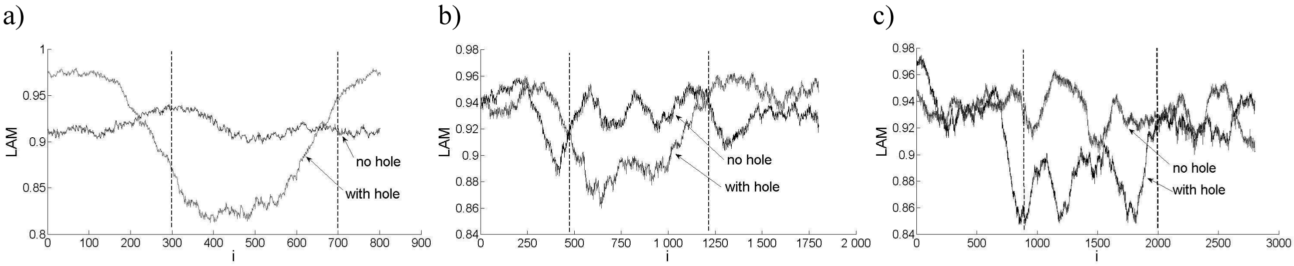

Fig. 7. Laminarity LAM of recurrence plot: a) with hole diameter ϕ 2 mm (m = 5, d = 8, ε = 20) and without hole (m = 4, d = 8, ε = 20), b) with hole diameter ϕ 4 mm (m = 4, d = 9, ε = 20) and without hole (m = 4, d = 9, ε = 20), c) with hole diameter ϕ 6 mm (m = 4, d = 9, ε = 20) and without hole (m = 4, d = 9, ε = 20)

Rys. 7. Laminarność LAM dla wykresu rekurencyjnego: a) z otworem o średnicy ϕ 2 mm (m = 5, d = 8, ε = 20) i bez otworu (m = 4, d = 8, ε = 20), b) z otworem o średnicy ϕ 4 mm (m = 4, d = 9, ε = 20) i bez otworu (m = 4, d = 9, ε = 20), c) z otworem o średnicy ϕ 6 mm (m = 4, d = 9, ε = 20) i bez otworu (m = 4, d = 9, ε = 20)

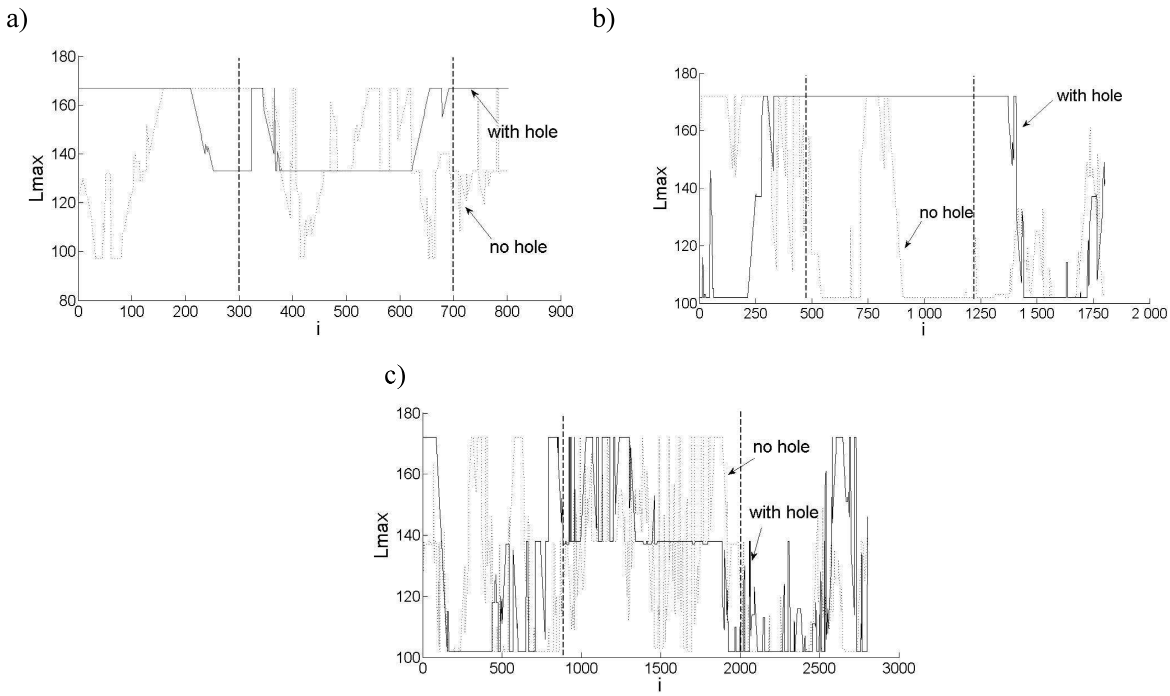

Fig. 8. Length of longest diagonal line L_{max} of recurrence plot: a) with hole diameter ϕ 2 mm (m = 5, d = 8, ε = 20) and without hole (m = 4, d = 8, ε = 20), b) with hole diameter ϕ 4 mm (m = 4, d = 9, ε = 20) and without hole (m = 4, d = 9, ε = 20), c) with hole diameter ϕ 6 mm (m = 4, d = 9, ε = 20) and without hole (m = 4, d = 9, ε = 20)

Rys. 8. Najdłuższa długość linii przekątnej (L_{max}) dla wykresu rekurencyjnego: a) z otworem o średnicy ϕ 2 mm (m = 5, d = 8, ε = 20) i bez otworu (m = 4, d = 8, ε = 20), b) z otworem o średnicy ϕ 4 mm (m = 4, d = 9, ε = 20) i bez otworu (m = 4, d = 9, ε = 20), c) z otworem o średnicy ϕ 6 mm (m = 4, d = 9, ε = 20) i bez otworu (m = 4, d = 9, ε = 20)

The obtained results and the quantification analysis show that it is possible to detect artificial defects in the form of through holes from a diameter of ϕ 2 mm.

CONCLUSIONS

The study of artificial defects in the form of holes can answer whether recurrence plots and recurrence quantifications can detect defects. RP diagrams and RQA analysis clearly show the differences in the recurrence diagram and the quantification characteristics. The quantifications that can detect a defect/damage are determinism, the clustering coefficient and laminarity. However the RQA shows that some quantifications such as the length of the longest diagonal line cannot be used as a defect detector.

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