RECURRENCE PLOT AND ITS QUANTIFICATION ANALYSIS APPLIED TO THE MONITORING AND SURVEILLANCE IN NUCLEAR POWER PLANTS

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\textbf{ABSTRACT}

The application of non-linear dynamic methods in many scientific fields has demonstrated its great potentiality in the early detection of significant dynamic singularities. The introduction of these methods oriented to the surveillance of anomalies and failures of nuclear reactors and their fundamental equipment have been demonstrated in the last years. Specifically, Recurrence Plot and its Quantification Analysis are methods currently used in many scientific fields. The paper focuses its attention on the estimation of the Recurrence Plots and its Quantification Analysis applied to signal samples obtained from different types of reactors: research reactor TRIGA MARK-III, BWR/5 and PHWR. Different behaviors are compared in order to look for a pattern for the characterization of the power instability events in the nuclear reactor. These outputs have a great importance for its application in systems of surveillance and monitoring in Nuclear Power Plants. For its introduction in a real time monitoring system, the authors propose some useful approaches. The results indicate the potentiality of the method for its implementation in a system of surveillance and monitoring in Nuclear Power Plants. All the calculations were performed with two computational tools developed by Marwan: Cross Recurrence Plot Toolbox for Matlab (Version 5.7, Release 22) and Visual Recurrence Analysis (Version 4.8).

\textbf{1.-INTRODUCTION}

The safety of a Nuclear Power Plant represents a thematic continually analyzed by the scientific community. The dynamical characterization of the reactor is extremely complex, mainly if during its operation appears an oscillatory process with great non-linear character contribution. These non-linear oscillatory processes are described and characterized by the use of non-linear tools. Some authors of this paper (ARN & MEMO) published in 2002 the application of non-linear tools as a representative approach to characterize the power instability in the reactor operation. In that case, the attractor dimension (AD) was applied in order to process the neutron noise signals and the authors suggested a new method based on its estimation calculating the second derivative of the integral correlation called: Automatic AD Quantitative Estimation (A-AD-QE). The application of this method brought satisfactory results, nevertheless, the noisy presence in this kind of signals hinder the AD estimation [6, 7]. In order to solve this problem, the Recurrence Plot (RP) and its quantification analysis (RQA) are applied. The advantages
of this method reside in the possibility to qualify and to quantify the oscillatory dynamics that is analyzed. Additionally, the visual information that is obtained, facilitates the interpretation of the oscillatory dynamics, improving the confiability of the diagnostic process.

The RP and its quantification through RQA in this work is applied to signals sampled in three different type of reactors: 1.- Induced instability in the research reactor type TRIGA MARK-III; 2.- Power instability in the reactor type BWR/5 and 3.- Vibration of internal component of reactor core PHWR). In all cases, analyzed datas were sampled by means of neutron detectors, installed in the nuclear reactor core of different construction technologies. In the measurement set, signals coming from the neutron detector and then the analogical antialising filters is applied. Later signals are converted digitally by an ADC.

2. THEORETICAL BACKGROUND

2.1.- Recurrence Plots

RP is a non-linear method that arise as an effective alternative for the graphical interpretation of the recurrence of states \( \mathbf{x}_i \) in the reconstructed dynamic in the multidimensional PS \([1]\). Higher dimensional PS can only be visualized by its projection into 2 or 3D sub-spaces. The advantage of RP introduced by Ekmann is the possibility to analyze the \( m \)-dimensional PS trajectory through a 2D representation of recurrences. Also, RPs can be applied to short and even nonstationary data \([1, 3, 4, 5]\). Just suppose, from the mathematical point of view, that the analyzed dynamic system is represented by the trajectories

\[
\{ \mathbf{x}_i \},
\]

where \( \mathbf{x}_i \in \mathbb{R}^m \), and \( m \) is the embedding dimension of the system, the recurrences can be expressed as:

\[
R_{ij}^{m, \varepsilon} = \Theta\left( \varepsilon - \left\| \mathbf{x}_i - \mathbf{x}_j \right\| \right), \quad i, j = 1, \ldots, N,
\]  

(1)

where \( N \) is the number of considered states \( x_i \), \( \Theta(\cdot) \) is the Heaviside function, \( \left\| \cdot \right\| \) is the norm and \( \varepsilon \) is a threshold distance. RP representation is a function of many variables: lag time (\( \tau \)), embedding dimension (\( m \)) and threshold distance (\( \varepsilon \)). The right definition of these variables allows the appropriate visualization of the RP, taking into account the oscillatory process in study. Nowadays some computational tools are available to implement these descriptors. More details about these tools can be found in (http://www.recurrence-plot.tk). In the present work, the application of RP and its quantification was executed by the Cross Recurrence Plot Toolbox for Matlab (Version 5.7, Release 22) developed by \([4]\). For the RP texture plot a Kononov Software, version 4.8 was used \([2]\).

2.2.1.- Recurrence plot representation. Lineal structure in RPs

The RP configuration offers a global and local vision of the reconstructed PS trajectories behavior. One point \( x(i) \) can be compared with a similar one in a multidimensional space. From the global point of view, the RP structures provide different behaviors along the whole reconstructed PS. From the local point of view, RP is able to extract local typical behaviors (singularities), which can appear or not in the future. Commonly, the RP is represented through black and white dots \((i, j)\), where black dots mark a recurrence and both axes are time axes. Instead of plotting the recurrences with black points, the distances (see Eq. 2) between the status \( \mathbf{x}_i \) and \( \mathbf{x}_j \) can be plotted (distance plot). This representation is known as global recurrence plot \([12]\) or unthresholded plot. This kind of plot helps to study phase space trajectory and can be use as orientation in the definition of an appropriate threshold value (Eq. 2).
\[ D_{i,j} = \| \tilde{x}_i - \tilde{x}_j \| \]  

To characterize the image reported by the RP it is necessary to consider that the time series are analyzed as a multidimensional set of points and the recurrences is performed in all embedded space, as a function of the selected threshold. In the RP is reflected the relative position of the point "i" with the point "j", which implies that the point "i" is compared with all the points "j". It is mean that with RP application a global comparative analysis of the PS is carried out. This global comparative analysis confers to the RP important advantages with regard to the PSP. Topological structure of the RP always evidences a main diagonal called Line of Identity (LOI), which is the result of the comparison of the point "i" with the "j" when \( i = j \). In this case the distance is 0 (see Ec. 4) and the point is assumed as black. This indicates that in the proximity (vicinity) of the LOI should be appeared the local singularities.

The closer inspection of the RPs reveals small scale structures which are characterized by the appearance of the following behaviors: single, isolated recurrence points; diagonal lines; vertical lines (horizontal) and vertical and horizontal lines / clusters. Examples in which it is possible to observe the application of the Recurrence Plots and its quantification can be found in [4].

III. RESULTS AND DISCUSSIONS OF RECURRENCE PLOT APPLICATION.
QUALITATIVE ADVANTAGES

The first analyzed group of signal belong to the research reactor with induced instability by mean of oscillatory control-rod. Fig. 2 shows a RP texture and PSP behavior. As it can be observed, the RP texture is characterized by the presence of parallel lines in both side of the LOI. At the qualitative point of view, RP demonstrates its advantage over the structure of the 3D PSP, which is represented in this figure by two different ways: lines and points. Another advantage of RP is its possibility to detect singularities (local particularity in the signal) over the all signal. The singularity detection can be used, also, to qualify the measurement set and to identify clearly the instability process over the all signal (beginning, duration and end).

![Figure 2.- RP and PSP of neutron noise signal sampled in the research reactor with induced instability process.](image-url)
One example of the singularity detection by RP can be shown in Fig. 2. In this figure, can be defined intervals by the same behavior (positions 1, 2, 3 and 4). Considering the market positions in the RP, duration of time intervals of these positions can be plotted. As it can be observed in Fig. 3, behavior of obtained plot for all selected intervals shows a high coincidences, which is corroborated with the RP texture (see Fig 2).

![Figure 3.- Plot of the singularities detected by RP visual inspection for the induced power instability in the research reactor type TRIGA MARK-III.](image)

The second analyzed groups of signals belong to BWR/5, in which appear a power instability event. The noise neutron signal, RP and PSP are showed in Fig. 6. In this figure, due to the stochastic nature of the neutron noise, the power instability detection is not possible by means of the signal and by the PSP.

![Figure 4. Neutron noise signal sampled in the BWR/5 and its RP and PSP during the event of power instability process.](image)

As it can be observed in Fig. 4, it is possible to perform a local characterization of the analyzed signal by RP texture. By means of PSP it’s not possible to determine duration and intensity of the oscillatory event.

For the third group of signals of the vibrational study of internal of the reactor type PHWR and their components, the 3D PSP configuration does not give any information of local changes of the oscillatory
system. In this kind of signals, as a qualitative point of view, by means of RP texture can be detected, also, singularities.

3.1.-Recurrence Quantification Analysis (RQA)

Quantification process by RQA is applied to all previous analyzed signals in this work. It is important to remark, that the sampled dynamics were taken in different reactor types. All the parameter used for the RQA application: \( m, \tau, \varepsilon \), window size and window step, were taken according to the studied case.

The first example is the application of RQA to the induced power instability in the research reactor type TRIGA MARK-III (Fig. 5 -A). The parameters used to quantify the RP texture were the following: \( m=1, \tau=1, \varepsilon=1\sigma \), window size=50 and window step= 5. In this figure, are plotted RR, DET and LAM. As it can be observed, the maximum coincide with the singularities detected in a qualitative analysis of the calculated RP for the same signal (see Fig. 2). It is important to remark, that the obtained values for the DET are close to 1, which means that the oscillatory process tend to be periodic over all the signal. A particular behavior of these variables can be found for the second and for the third groups of signal. For instance, for the second group with parameters for the RQA: \( m=1, \tau=1, \varepsilon=0.5\sigma \), window size: 50 and window step=5 behaviors of calculated variables corroborate the RP morphology and could be used to estimate, in a quantitative way, the degree of the reactor power instability. This approach should be analyzed deeply and in an integral way in future studies.

![Fig. 5.- A- RQA applied to the noise neutron signals sampled in a research reactor type TRIGA MARK-III during the induced power instability (left side: RR, DET and LAM); B- RQA for the BWR/5.](image)

The quantification of parallel lines to the LOI by the RQA is profitable way for the evaluation of periodic behaviors of a signal. One very useful variable for the quantification is DET plotted vs Time. In this case minimizing this function, it is possible to define the lower presence of the parallel lines (periodicity) to the LOI over the all signal. Specifically, for the analyzed time series of BWR/5, the \( \min\{DET \text{ vs Time}\} = 54.73\% \).
3.- CONCLUSIONS

The analysis of the RP texture and its quantification analysis, RQA, demonstrated its potentiality for the detection and monitoring of the oscillatory processes in the nuclear reactors. Their efficient application in reactors of different technologies and for a considerable groups of noise neutron signals allow to extend the results to other type of reactors, independently of its technology. In a particular case of the power instability the detection by RP and its quantification by RQA is of high importance for the safety and confiability of nuclear reactor. The results of the developed method verify that it is possible to detect oscillatory processes of power (instabilities) and to distinguish them of the stable work of the reactor. It is important to remark the potentiality of the RP application in the characterization of the internal vibration of the reactor core. The qualification and quantification of these vibrational indications can be used as a symptom parameter of conditioning monitoring in the nuclear reactors.

The studied cases en the present work showed the the hight sensitivity of the RP texture and its quantification by RQA. Its implementation in “ON LINE” monitoring system is possible, but it requires of an exhaustive evaluation of the obtained patterns for each variable.

REFERENCES