# Application of Chaotic Recurrence Plot Analysis to Identification of Oil/Water Two-Phase Flow Patterns

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**Abstract.** Recurrence quantification analysis method was employed to study the identification of oil/water two-phase flow patterns. The results showed recurrence plot appeared different textures for the transitional oil/water two phase flow patterns, and was special for different flow pattern. That indicated the texture of recurrence plot was sensitive to the changes of oil/water two flow patterns, and the recurrence quantification analysis is a useful diagnosis tool in identifying of two phase flow patterns.

**Keywords:** Oil/water two-phase flow, flow pattern, recurrence plot, recurrence quantification analysis.

## 1 Introduction

Two phase flow widely exist in many production processes, such as chemical engineering, petroleum industry and other fields. Especially, oil/water two phase flow phenomena are very common in production oil wells. Four flow patterns of oil/water two phase flows can be seen in vertical upward pipe (bubble, slug, froth, mist). The transitional mechanisms between these flow patterns are very complex, and the flow pattern identification is still a very difficult problem. Recently, the recurrence plot (RP) and the recurrence quantification analysis (RQA) methods [1-2] become a new powerful tool to chaotic time series analysis, and many applications in different fields have been developed [3-5]. In this study, we investigated the RP and RQA methods based on the Lorenz chaotic system [6], and then applied the method to conductance fluctuating signals analysis of oil /water two phase flow in order to find a quick look flow pattern identification method.

## 2 Recurrence Plot and Recurrence Quantification Analysis

### 2.1 Recurrence Plot (RP)

Phase space reconstruction is a necessary step in chaotic time series analyzing. According to the Takens's embedding theorem, we need to set a time delay to a

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one-dimension time series to reconstruct its phase space. If the original time series is expressed with X($x_1$, $x_2$, $x_3$, ……, $x_n$), after phase space reconstruction with m-dimension embedding and $\tau$ -time delay, the vector number is

$$N = n-(m-1)\tau \tag{1}$$

The distance between any two vectors is defined as

$$d_{i,j} = \left\| \boldsymbol{X}_i - \boldsymbol{X}_j \right\| \tag{2}$$

And the threshold is defined as

$$\varepsilon = \alpha \cdot std(\boldsymbol{X}) \tag{3}$$

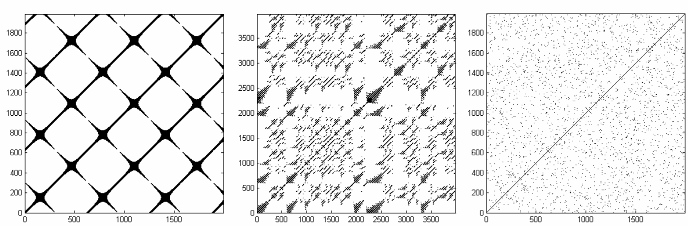
Where $std(\boldsymbol{X})$ is the standard deviation of time series $\boldsymbol{X}$ , $\alpha$ is a constant coefficient which is generally about 0.15. Then the recurrence matrix is expressed by

$$\boldsymbol{R}_{ij} = \Theta(d_{i,j} - \varepsilon) \tag{4}$$

Where:

$$\Theta(x) = \begin{cases} 1, x < 0 \\ 0, x > 0 \end{cases} \tag{5}$$

We define recurrence point at the place where the value is 1 in the recurrence matrix $\boldsymbol{R}_{ij}$, and then dot them on the coordinate plane to get an $N \times N$ plane plot-recurrence plot (RP). The typical recurrence plots of sine signal, Lorenz chaotic signal and random noise signal according to the definition above are showed in Fig. 1, the RP pattern differences are very obvious, and the recurrence plots can sensitively reflect the signals from different physical background.




(a) sine signal (b) Lorenz strange attractor (c) random noise signal

**Fig. 1.** Recurrence plot of three different signals

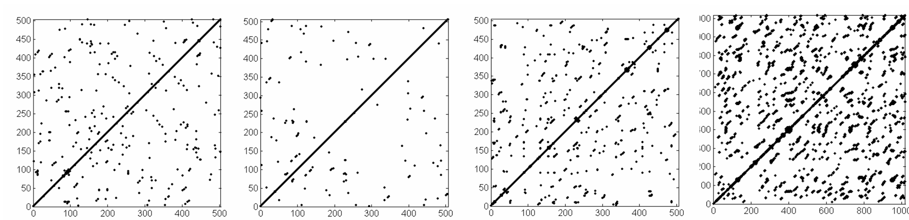
## 2.2 Recurrence Quantification Analysis (RQA)

Recurrence quantification analysis was developed based on the recurrence plot, and the detailed texture of recurrence plot can be extracted. From the RP shown in Fig. 1, we can see that the main texture of RP is the recurrence points distributed in the coordinate plane and the parallel lines in the diagonal direction constructed by the points in neighborhood. The feature values of RP can be characterized [2] with Recurrence Rate (RR), Determinism (DET), Ratio, The average diagonal line length (L), the maximum length (Lmax), Divergence (DIV), Entropy (ENTR).

# 3 Chaotic Recurrence Plot Analysis of Oil/Water Two-Phase Flow Patterns

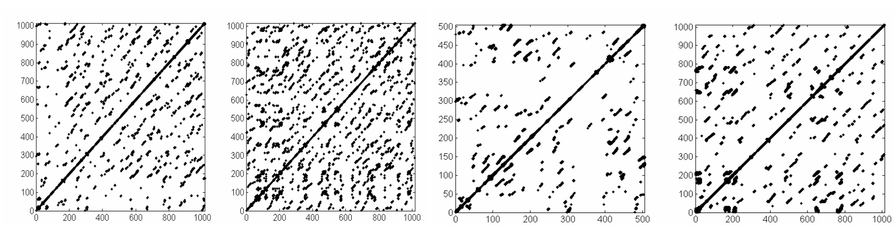
## 3.1 Recurrence Plot Analysis of the Transitional Flow Pattern

Because the oil/water two phase flow with water cut of 51% (51.5%) belongs to low dimension chaotic system [7], its RP is not sensitive to the embedding dimension. We choose the embedding dimension $m$ = 3; and choose the time delay based on the first minimum of mutual information method [8]. Considering the noise in the experiment data when computing the recurrence matrix, we choose a relatively large threshold coefficient($\alpha$=0.2), and the RP are shown in Fig.2. We can see that the total flow rate of oil/water two phase flow has significantly influence on the texture of RP. At the low flow rate (20m$^3$/day and 40m$^3$/day), the texture of diagonal line type on the RP almost does not exist and the texture of dispersed points appears on the RP; however, at the high flow rate (50m$^3$/day), the texture of diagonal line type appears obviously. The phenomenon that two different kind textures appear on the RP corresponds to the character of transitional flow pattern with water cut of 51% (51.5%) that oil-in-water or water-in-oil appears randomly [7].



(a) Qt=20m$^3$/d Kw=51.5% (b) Qt=40m$^3$/d Kw=51.5% (c) Qt=40m$^3$/d Kw=51% (d) Qt=50m$^3$/d Kw=51%

**Fig. 2.** Recurrence plots for transitional flow patterns



(a) Qt=10m$^3$/d Kw=91% (b) Qt=20m$^3$/d Kw=91% (c) Qt=40m$^3$/d Kw=81% (d) Qt=30m$^3$/d Kw=71%

**Fig. 3.** Recurrence plots for oil-in-water flow patterns

### 3.2 Recurrence Plot Analysis of Oil-in-Water Flow Pattern

Fig.3 shows the RP of oil-in-water flow pattern. They are greatly different from the RP of transitional flow pattern with water cut of 51% (51.5%). On the RP, the diagonal line type texture is only appeared, but not dispersed points. It indicates that the oil-in-water flow pattern is relatively steady, and its flow character is not easily changed with different flows.

## 4 Conclusions

We used the time series data generated by the Lorenz equation to verify the validity and sensitivity of recurrence quantification analysis, and then applied this method to the identification of oil/water two-phase flow patterns. The research indicated that the texture of dispersed point or diagonal line type was appeared on recurrence plot for the transitional oil/water two phase flow pattern; however, the diagonal line type texture was only appeared for the oil-in-water flow pattern. This phenomenon showed that the texture on recurrence plot was sensitive to the changes of oil/water two flow patterns, and the recurrence quantification analysis is a valid supplementary diagnosis tool for flow patterns identification.

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