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# RECURRENCE QUANTIFICATION ANALYSIS: A SIMPLE METHOD FOR CHARACTERIZATION OF VARIOUS STRUCTURES IN GAS-SOLID FLUIDIZED BEDS

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## ABSTRACT

A combination of the multi-scale method and the nonlinear analysis method was developed to study the complexity of fluctuation dynamics in fluidized bed. Pressure fluctuations were measured in a fluidized bed of 0.15 m in diameter for sands with mean diameters of 150, 300 and 600 micron and were analyzed using nonlinear recurrence quantification analysis. The results show that RQA can be used as an effective approach to characterize multi-scale flow behavior in the gas-solid fluidized bed.

## INTRODUCTION

Gas-solid fluidized beds are one of the most complicated hydrodynamic processes. Typical particle-fluid flow patterns exhibit nonlinear and nonequilibrium dynamic characteristics with heterogeneous flow structures (1). Due to the complexity of interactions between particles and fluid, hydrodynamic of fluidized beds has been intensively studied (1-7). Consequently, further studies are still required to understand fluidization phenomena and develop more accurate quantitative models used in design and optimization of fluidized-bed reactors. Li and Kwauk (8) demonstrated that the complex dynamics of a fluidized system may be presented as three different structures in fluidized beds based on multi-scale approach: macro structures of high amplitude and low frequencies (up to 3 Hz) corresponding to large scale phenomena such as large bubbles and bed surface oscillation, meso structures with frequencies in the range of 3–20 Hz referring to clusters and small bubbles and micro structures of high frequencies of 20–200 Hz (Nyquist frequency) originating from impacts of solid particles, their motion and measured noise in the fluidized bed.

Hydrodynamic of fluidized bed is considered to be nonlinear (6, 9-10). The main idea of multi-scale structures is also nonlinearity. Consequently, a combination of the multi-scale method and the nonlinear analysis method is required to study the complexity of fluctuation dynamics in fluidized bed. In recent years, state space chaos analysis has been proposed to study the complex dynamics of a fluidization system through identifying different scales of structures. This technique has found

many applications in fluidized beds (1, 11-12). The concept of recurrence plot (RP) and recurrence quantification analysis (RQA), which relies on the presence of recurring/deterministic structures underlying the data, was recently introduced for the chaos analysis. Recurrence is a basic property of dynamical systems, which can be exploited to describe the behavior of the system in the phase space. Tahmasebpour et al. (7) and Babaei et al. (13) demonstrated that RP and RQA are potent tools to study the hydrodynamics of fluidization. However, yet combination of the multi-scale method and the RQA for studying the complexity of hydrodynamics of fluidized systems has not been developed. In this paper, RQA has been developed for studying the complexity of structures in fluidized beds.

## EXPERIMENTAL METHODS

The experiments were carried out in a gas–solid fluidized bed made of a Plexiglas column of 15 cm inner diameter and 200 cm height. Air at room temperature was entered into the column through a perforated plate distributor of 435 holes with 7-mm triangle pitch and its flow rate was controlled by a mass flow controller. A cyclone, placed at the column exit, would return the entrained solids back to the bed. The static bed height in experiments was set to 22.5 cm ( $L/D=1.5$ ) and superficial gas velocity was varied in the range of 0.1 to 1.6 m/s. Sand particles (Geldart B) with mean size of 150, 300 and 600  $\mu\text{m}$  and a particle density of 2640  $\text{kg/m}^3$  were used in the experiments.

Pressure probe (model SEN-3248 (B075), Kobold Company) was screwed into the gluing studs located 20 cm above the distributor. This probe has a response time of less than 1 millisecond. The measured signals were band-pass filtered at lower cut-off frequency of 0.1 Hz and upper cut-off Nyquist frequency (200 Hz). The filtered signals were then amplified with a gain of 100. The pressure transducer was connected to a 16 bit data acquisition board (Advantech 1712L). The sampling frequency for pressure fluctuations was 400 Hz. Total number of data points in each sample was 120000, corresponding to about 300 seconds of the sampling time.

## METHOD OF ANALYSIS

### RECURRENCE PLOT

Eckmann et al. (14) introduced the RP as a graphical tool that can visualize the recurrences of dynamical systems. Usually, a phase space is a high dimensional space and can only be visualized by projection into the two or three dimensional sub-spaces. Eckmann's tool makes it possible to investigate the  $m$ -dimensional phase space trajectory through a two-dimensional representation of its recurrences. RP is a 2-dimensional plot mathematically expressed as:

$$R_{i,j} = \Theta(\varepsilon - \|x_i - x_j\|) \quad i, j = 1, 2, 3, \dots, N \quad (1)$$

where  $N$  is the number of considered states,  $x_i, x_j \in R^d$  represent the  $i$ -th and  $j$ -th points of the  $d$ -dimensional state space trajectory,  $\| \cdot \|$  represent the norm,  $\varepsilon$  is a threshold distance and  $\Theta$  is the Heaviside function. RP is obtained by plotting the recurrence matrix, Eq. (1): if  $R_{i,j} = 1$  it is considered as a recurrence point and

appears as a black dot at the coordinates (i, j), if  $R_{ij} = 0$  it forms a white dot. March et al. (15) showed that the RP can be constructed without embedding. Thus, it was thought desirable to choose the embedding parameters of 1 based on the Takens' theorem (16).

## RECURRENCE QUANTIFICATION ANALYSIS

The RQA was developed in order to quantify differently appearing RPs based on the small-scale structures therein. RQA involves estimation of some parameters that describe the structures in RPs such as single dots, diagonal and vertical (or horizontal) lines (17). Recurrence rate, determinism and laminarity are some of RQA variables that were used in this study.

Recurrence rate (RR) expresses the density of recurrence points throughout the trajectory and physically corresponds to the probability that a specific state of the system will recur. Recurrence rate is mathematically defined as:

$$RR = \frac{1}{N^2} \sum_{i,j=1}^N R_{i,j} \quad (2)$$

where  $N$  is the length of the time-series under analysis.

Determinism (DET) measures the fraction of repeated points forming diagonal line structures. Diagonal lines shorter than  $l_{min}$  (usually  $l_{min} = 2$ ) are not considered during the calculation of DET. Determinism is defined as:

$$DET = \frac{\sum_{l=l_{min}}^N l.P(l)}{\sum_{l=1}^N l.P(l)} \quad (3)$$

Length of a diagonal line ( $l$ ) is defined as the number of its black dots and  $\sum l.P(l)$  represents the number of black dots forming diagonal lines. Determinism is related to predictability of a system. For example, determinism is low for a stochastic system and is high for a periodic system.

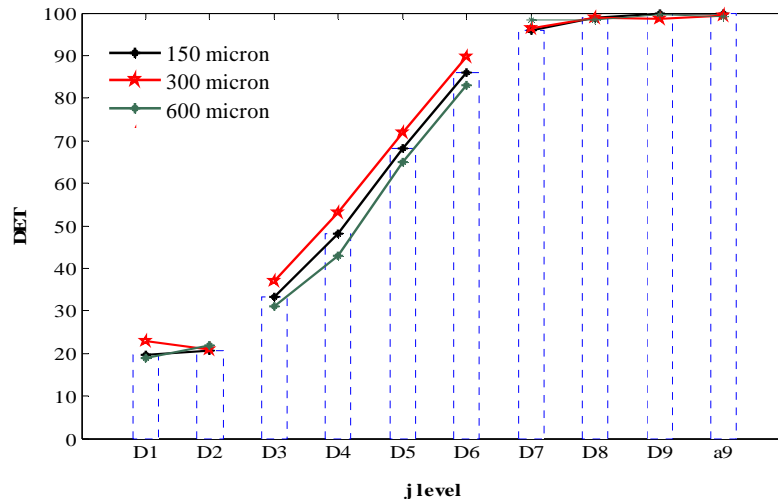
The third recurrence descriptor is laminarity (LAM), which is the fraction of recurrence points forming vertical (or horizontal) lines with length of  $v$ . It is physically related to the amount of laminar states in the system. A vertical/horizontal line marks a length in which a state does not change or changes very slowly. Laminarity is given by:

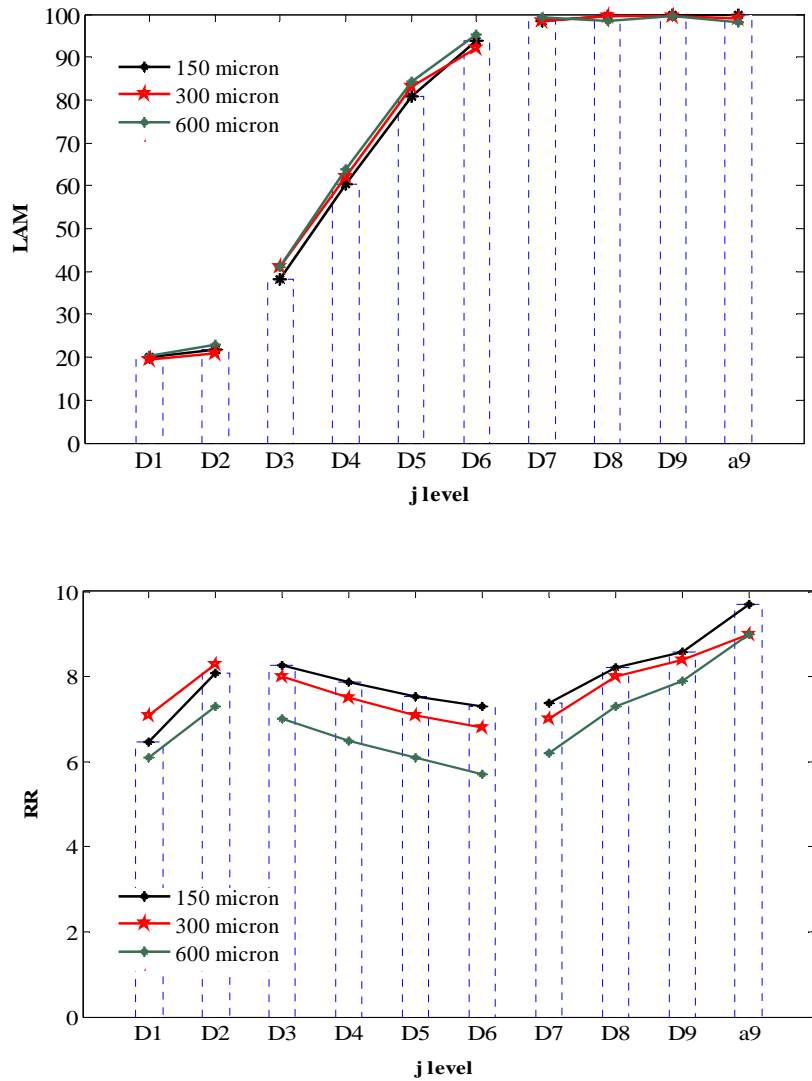
$$LAM = \frac{\sum_{v=v_{min}}^N v.P(v)}{\sum_{v=1}^N v.P(v)} \quad (4)$$

where  $\sum v.P(v)$  is the number of points forming vertical (or horizontal) lines. Usually,  $v_{min} = 2$  is an appropriate value. Due to symmetrical feature of the RP, the number and length of horizontal and vertical lines are equal (17).

## RESULTS AND DISCUSSION

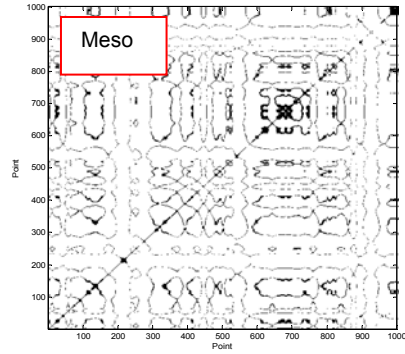
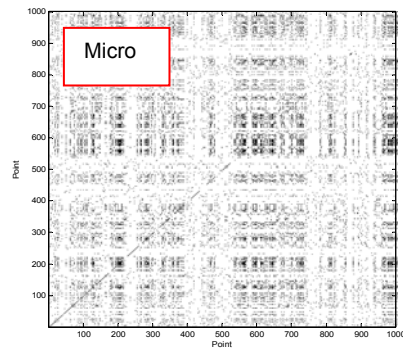
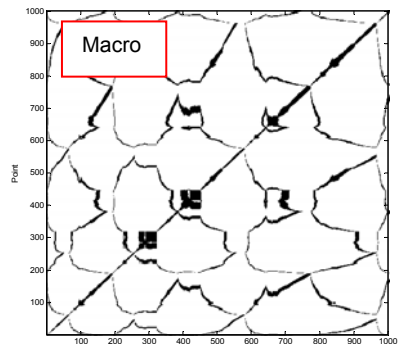
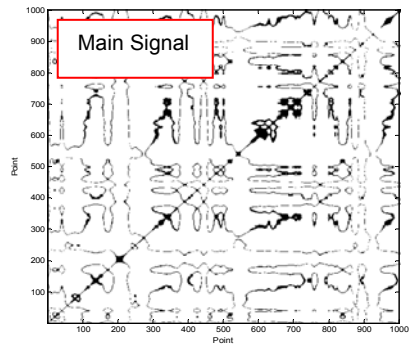
There are different suggestions in literature for selection of the  $j$  levels corresponding to micro, meso, and macro structures in fluidized beds (1, 18). In this study, pressure fluctuation signals, representing micro-scale, meso-scale and macro-scale structures, were obtained by investigating the similar RQA characteristics for different  $j$  levels of pressure signals. Fig. 1 shows DET, LAM and RR of the pressure fluctuations at different  $j$  levels. As can be seen in these figures, the variations in DET and LAM are similar and three regions can be observed with increasing the  $j$  levels. It has been shown that with increasing the portion of macro structures in the fluidized bed, the pressure signal exhibits a periodic behavior (7), thus, DET and LAM increase. On the other hand, the micro structures have the least periodicity and consequently their DET and LAM are the lowest. This is because of this fact that finer structures like solid particles impacts, their motion, small bubbles and clusters mostly show stochastic behaviors (11). For instance, particles impacts do not have periodic and deterministic essence. Therefore, it can be concluded that levels 7, 8 and 9 detail and level 9 approximation signals represent the macro-scale structures of the bed. Levels 1 and 2 of detail signals represent information about the micro structures and levels 3, 4, 5, and 6 of detail signals correspond to meso-scale structures. Unlike the constant trend of laminarity and determinism for macro and micro structures at different  $j$  levels, DET and LAM of meso structures increase with increasing  $j$  levels. This is probably due to the fact that meso structures consist of much more phenomena in comparison with other structures. RR figure also reveals change of multi-scale structures in three points which is in good agreement with DET and LAM figures. Therefore, it can be claimed that the RQA is capable of recognizing the multi-scale structures for pressure signals measured in fluidized beds. These conclusions are in good agreement with the results in the literature (1).



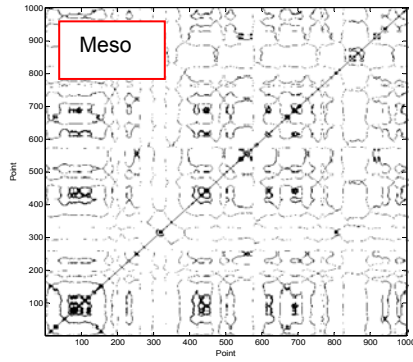
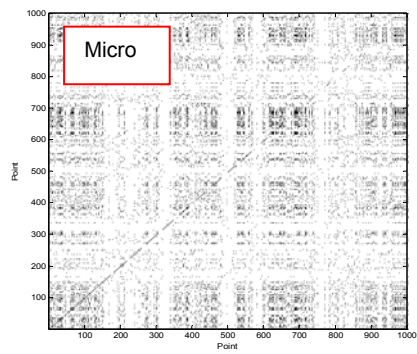
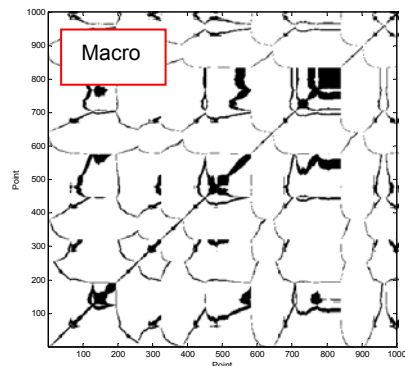
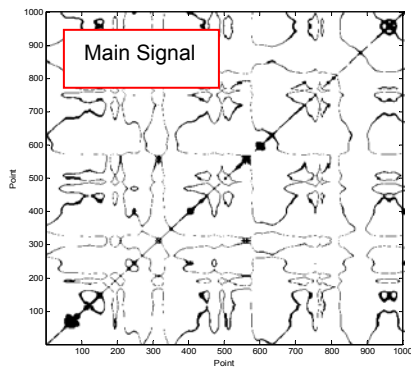


**Figure 1** DET, LAM and RR of the pressure fluctuations at different  $j$  levels for 150, 300 and 600 sand particles at  $L/D=1.5$

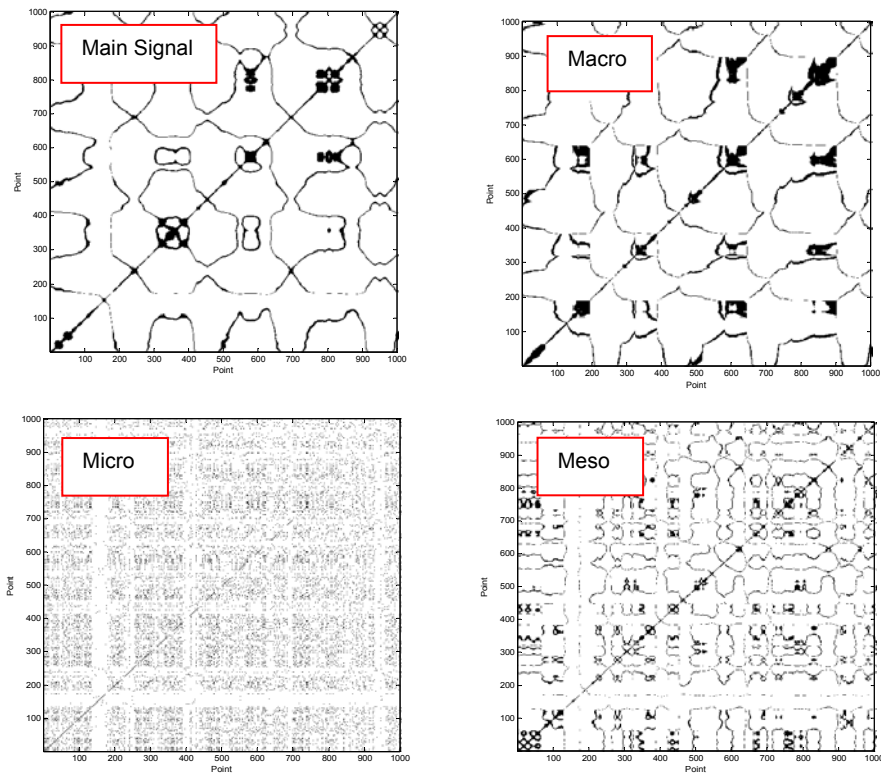
RPs for macro, meso, micro structures and also main signals measured for 150, 300 and 600  $\mu\text{m}$  sand particles at  $L/D=1.5$  and  $U=0.5$  m/s are presented in Figs. 2a-c. As can be seen in these figures, meso structures have the considerable contribution in compare to the macro and micro structures for 150 micron sands. Contribution of macro structures increases for 300 micron sands and the most important structures for 600 micron sands are macro structures. In other words, the macro structures are of more importance for 600 micron sands compared to 300 and 150, since the RP of main signal is more similar to the macro structure rather than the other two. This trend shows that larger particles produce larger and more stable bubbles.



(a)



(b)



(c)

**Figure 2** RPs for macro, meso, micro structures and also main signal measured for 150 (a), 300 (b) and 600 (c)  $\mu\text{m}$  sand particles at  $L/D=1.5$  and  $U=0.5$  m/s

## CONCLUSIONS

DET, LAM and RR of the pressure fluctuations at different  $j$  levels represent micro-scale, meso-scale and macro-scale structures in a fluidized bed accurately. The results indicated that micro-scale can be presented by  $D1+D2$  (50-200 Hz), meso-scale by  $D3+D4+D5+D6$  (3.125-50 Hz) and macro-scale by  $D7+D8+D9+a9$  (0-3.125 Hz). Also RPs reveal that the contribution of macro structures increases by increasing the size of sand. In other words, larger particles produce larger and more stable bubbles.



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