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ATTRACTOR COMPARISON OF VIBRATION SIGNAL TO CHARACTERIZE OF HYDRODYNAMICS OF FLUIDIZED BEDS

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ABSTRACT
A new approach based on comparison of attractors of reference and evaluation time series has been presented for observing changes in the hydrodynamics of the fluidized beds. The experiments were carried out for three particle sizes, different velocities, and three probe heights. The measured signals of different sand, and aspect ratio were compared based on the null hypothesis whether they have the same origin or not. The results indicate that the S-statistics method can detect small changes in the particle size and aspect ratio of the sand. It was also shown that attractor comparison can be a reliable method for detecting regime transition, agglomeration and variation in the hydrodynamics of the fluidized beds.

INTRODUCTION
Fluidization as a process in which solid particles become suspended at enough fluid velocity has many applications in various industries. Some advantages such as high rates of mass and heat transfers, in comparison with the conventional packed beds, but fluidized beds have disadvantages which limit its industrial applications. Possible de-fluidization due to variation in the fluidized bed hydrodynamics which can occur by particles agglomeration and reduction of gas velocity, unexpected change in the hydrodynamics because of undesirable fluctuation in the excess gas velocity are some of these problems. Moreover, fluidization is one of the most complex systems in practical application. Therefore, accurate monitoring of hydrodynamic conditions is essential and reliable methods should be considered to determine hydrodynamic properties of the fluidized bed. Many intrusive and non-intrusive measuring methods have been applied to study the hydrodynamics of fluidized beds. Analysis of the time series of measurable signals is an applicable method. Many investigators have used some methods in time and frequency domains for the investigation of regime transition and hydrodynamic characteristics of the fluidized bed (1-4). Van den Bleek et al. (5) used the Kolmogorov entropy as a chaos analysis to study hydrodynamics of fluidized beds.

In this work, a new method is applied to investigate of fluidized bed hydrodynamics by analyzing the bed vibration signatures using the S-statistic method. This method was first applied by Van Ommen et al. (6) in order to detect agglomeration in early stages using pressure fluctuations. Here, this approach has been utilized to detect the variations in the bed hydrodynamic by comparing reconstructed attractors of the bed vibration signatures of different situations.

EXPERIMENTAL METHODS

The setup was a Plexiglas gas-solid fluidized of 15 cm inner diameter and 2 m height. The gas distributor is a perforated plate containing 435 holes. Air was supplied by a compressor and a cyclone was placed at the column exit to return the entrained solids back to the bed. Sand particles with mean size of 226, 470 and 700 µm and particle density of 2600 kg/m^3 were used in the experiments. The system was electrically grounded to decrease electrostatic effects.

The experiments were carried out with static bed heights of 7.5, 15 and 22.5 cm. Two identical DJB accelerometers model A/120/V with resonant frequency of 53 kHz and sensitivity of 100 mV/ms^{-2} were used to measure vibration signals. These measuring probes were mounted on the column at 5, 10 and 15 cm above the distributor by means of a magnet to minimize sudden fluctuations. To prevent wave interference and losing information, the sampling frequency (f_s) of vibration signals were set to 65 kHz (1-2). Before applying the analyses methods, high-frequency noises of the signal were reduced by applying a low-pass filter using Hamming window function of order 50 and a cut-off frequency of 20 kHz. Because of high sampling rate in the vibration measurements, existence of noise is unavoidable.

METHOD OF ANALYSIS

The S-statistic method uses a statistical test compare two delay vector distributions, this method introduced by Diks et al.(7). Parameter named as S where is the unbiased estimator of squared distance of two delay vector distributions in the state space is calculated using following equation:

$$S = \frac{\hat{Q}}{\sqrt{V_c(\hat{Q})}} \tag{1}$$

V_c is the variance of $\hat{Q}$. If S value is greater than 3, the null hypothesis is rejected with more than 95 % of confidence level, thus, the two distributions come from different origins. Van Ommen et al. (6) applied this test to detect variations in the reconstructed attractors obtained from time series of pressure fluctuations of a fluidized bed. An attractor is a representation of the dynamics of the system in the state space. As proved by Takens (8), by applying time delay embedding theory on measured values, the attractor of a system can be reconstructed using only a smoothed single measured variable of the system. This method has the ability to detect any changes which happen in the system such as agglomeration, regime transition due to change in the superficial gas velocity.

The performance of the method depends on three parameters which should be chosen properly: embedding dimension *m*, bandwidth *d* and segment length *l*. In this work, all the data points in the time window were used in order to use all the available information from time series. Selecting an appropriate embedding dimension is very important due to the fact that an incorrect embedding dimension would result in a reconstructed attractor that does not represent the real attractor of the system. In this work, the method of false nearest neighbors was used for selecting of this parameter (9-10). This method has nearly a simple algorithm. Next parameter to be set is the segment length which reduces the temporal correlation of the underlying data set. According to Theiler (11), the pairs of points which are close, not due to the attractor geometry, should be excluded. The time at which autocorrelation function approaches to zero can be used to determine appropriate value of *l*. As indicated by Diks et al. (7), the power of the test depends on the bandwidth *d*. Diks et al. (7) mentioned that this parameter should be selected at the trade-off of the relatively small value, where the test will pick up local differences between the two distributions, and too large values, where the delay vector distributions are smoothed.

RESULTS AND DISCUSSION

Fig. 1 shows the variation of percent of false neighbors as a function of embedding dimension. As can be seen in this figure, since the percent of false neighbors reaches to zero at the embedding dimension of 50, the embedding dimension was selected as 50 for the *S*-statistic test (12).

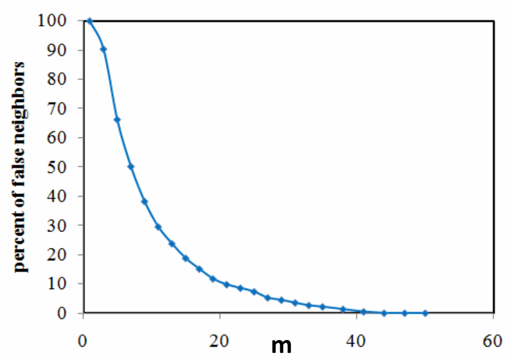

Figure 1 Percent of false neighbor versus embedding dimension

Fig. 2 indicates the autocorrelation function of a vibration signature versus delay lag. As can be seen, this value is approximately zero at delays 98 and thus, the value of *l* was set to 100. In other words, by selecting this value for segment length, data points are almost independent when they are separated by delays.

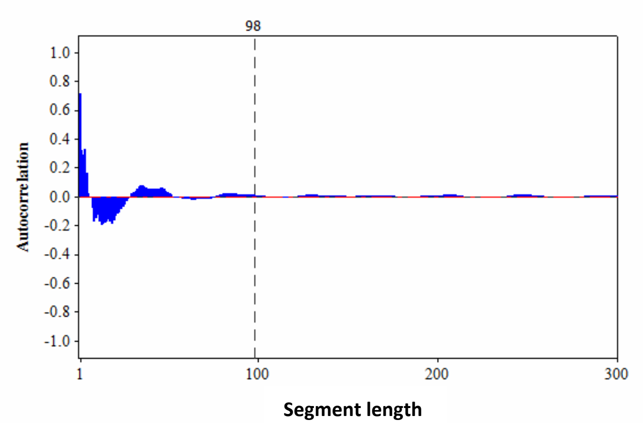

Figure 2 Autocorrelation function of a sample vibration signatures

Fig. 3 shows the behavior of S-value versus bandwidth. The curve is related to *S*-values calculated for several combinations of two bed vibration signatures obtained from different conditions. Since it is expected to obtain *S*-values greater than 3 for different signatures, the bandwidth was selected equal to 1.1 at which the limited deviations around this value have a small influence on the test outcome (6).

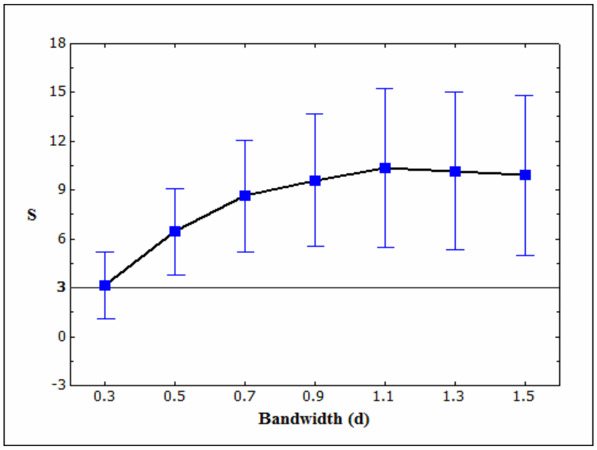

Figure 3 Behavior of *S*-values versus bandwidth

Detection of variation in the hydrodynamics of fluidized bed was performed by comparing the reconstructed attractor of each bed vibration signature with the one obtained from a different aspect ratio or size of sand. As can be seen in the Figs. 5 and 6, when two different sands or two different aspect ratios of sand particle compared with each other, *S*-values greater than 3 were obtained, which shows two signals origin from different hydrodynamics of the bed. This indicates that the structures which exist in the bed are changing. However, when two identical sands or aspect ratios are compared, S-values become less than 3, which indicate that no change has happened in the hydrodynamics of the fluidized bed. The reference signature for calculating of the S value in the Fig. 4 was selected at aspect ratio of 1, and the reference for attractor comparison in Fig. 5 was considered as sand 2 with mean diameter of 470 µm.

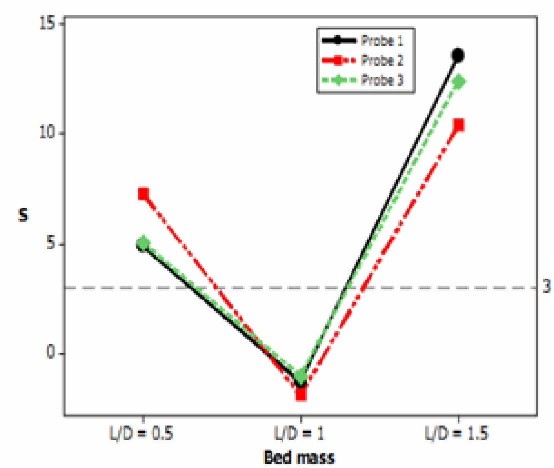

Figure 4 S-values of comparisons between vibration signatures of different Aspect ratio

The results show that attractor comparison can be a reliable method for characterization of gas solid fluidized bed hydrodynamics and this concept can be used to identify and to predict changes in the hydrodynamics of the fluidized bed.

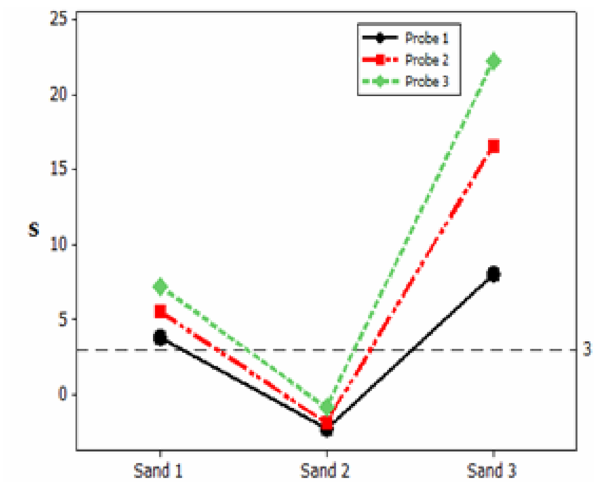

Figure 5 S-values of comparisons between vibration signatures of different size of sand

Fig. 6 shows the results of the comparison between reconstructed attractor of the reference and evaluation time series for two different velocities (0.6 m/s as a reference and 1.4 m/s as evaluation time series files). As it can be seen in this figure, the averages of the *S*-statistics value are above 3, which indicate that the time series are not originated from the same hydrodynamics. But as can be seen in Fig. 7, when two identical signals (U = 0.6 m/s) are compared with each other by this method and the values are below 3, which indicates that the time series are originated from the same hydrodynamics. Since the bed in the velocity of 0.6 m/s is in bubbling fluidization and 1.4 m/s as evaluation time series can be a representative of turbulent fluidization regimes. These results show the prediction of the regime transition is also another application of this method. The similar results which are obtained in another new publication confirmed the *S*-Statistics methods can be reliable methods to predict variation in hydrodynamics of the fluidized bed (12, 13).

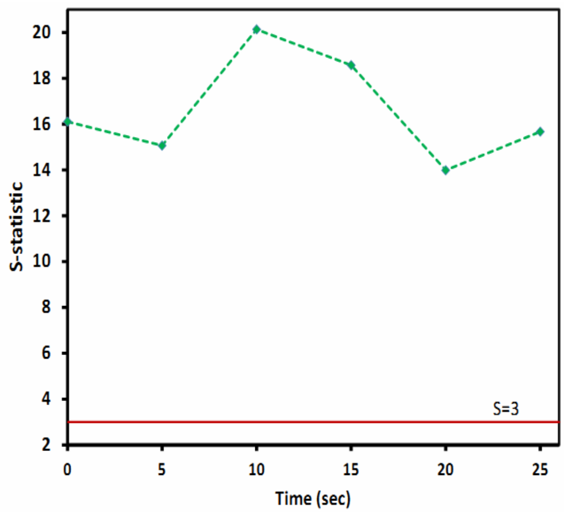

Figure 6 Comparisons between reconstructed attractors of reference and the evaluation time series for two different velocities of 0.6 m/s (bubbling region) and 1.4 m/s (turbulent region).

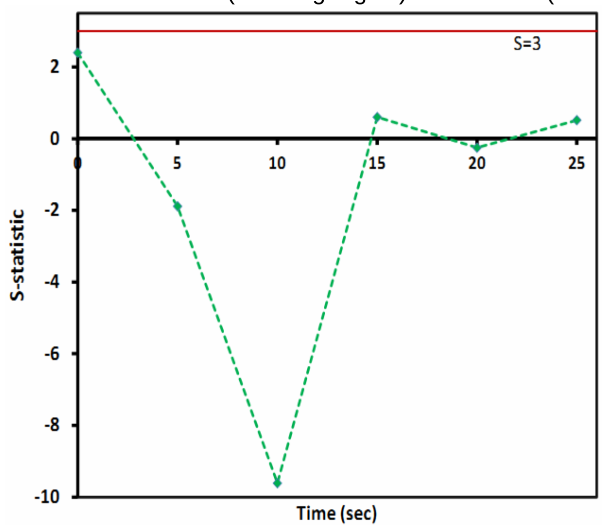

Figure 7 Comparisons between reconstructed attractors of reference and the evaluation time series for two identical velocities of 0.6 m/s in bubbling region.

CONCLUSIONS

A new approach is proposed to determine variation in the hydrodynamics of the fluidized bed. This method utilizes an approach named as S-statistic for chaotic comparison of vibration signatures measured in a lab-scale fluidized bed which can detect whether the signatures are originated from similar hydrodynamics or not. The results of comparisons between attractors of two vibration signatures at different aspect ratio and size of sand indicates that they were originated from different origins, and also the S-statistics method can be used to determine variation in the hydrodynamics of the fluidization.

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