Detecting regime transition velocity in fluidized beds using attractor comparison of vibration signals

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Abstract—Vibration signatures as the representatives of the fluidized bed nonlinear hydrodynamics were measured in a lab-scale fluidized bed of sand particles operated at ambient conditions. The experiments were carried out for three particle sizes, different velocities, and three probe heights. The S-statistic method was applied to the vibration signatures for the chaotic attractor comparison. The measured signatures of two different consecutive velocities in similar conditions were compared based on the null hypothesis that they have same origin. According to this method, when the value of S is larger than 3, the null hypothesis is rejected with the confidence level of 95% indicating that the two signals represents hydrodynamics. The results are compared with results obtained from common statistical methods and it is shown that attractor comparison can be a reliable method for detecting regime transition velocity.

INTRODUCTION

Fluidized beds operate at different regimes such as bubbling, turbulent and slugging depending on the application requirements and operating conditions. Since performance of fluidized beds is dependent on their hydrodynamics, many investigations were conducted to characterize the hydrodynamics of fluidized beds such as transition velocities. Pressure fluctuation measurement is one of the popular methods used by many researchers to characterize the hydrodynamics of the fluidized beds. Recently, a non-intrusive method based on measurement of vibration of the bed shell was proposed by Abbasi et al. to investigate the hydrodynamics of gas-solid fluidized beds. In addition to bubble changes and movements, bed vibration signals can also originate from particle-wall collisions which depend on particle size. Thus, the bed vibration signals contain useful information which can be utilized to characterize the bed hydrodynamics.

Several methods have been reported in order to determine regime transitions by analyzing time-series signals obtained from the fluidized beds. Lee and Kim used several statistical methods such as mean amplitude, fluctuation interval, standard deviation, skewness and flatness for analyzing pressure fluctuations of the fluidized bed in order to determine the transition velocity from bubbling to turbulent regime. A wavelet multi-resolution analysis was applied to absolute pressure fluctuations by Yang et al. in order to determine regime transition velocities and characterize the flow regimes. Van den Bleek et al. used the Kolmogorov entropy as a chaos analysis to study regime transitions in the fluidized beds. They stated that a dip in the Kolmogorov entropy indicates a regime transition from one regime to another.

In this work, a new approach is used to study transition from bubbling to turbulent regime by analyzing the bed vibration signatures using the S-statistic method. This method was first applied by Van Ommen et al. in order to detect agglomeration in early stages using pressure fluctuations. Here, detection of regime transition is performed by comparing reconstructed attractors of the bed vibration signatures of different velocities.
METHOD OF ANALYSIS

General description
The S-statistic method uses a statistical test proposed by Diks et al. to compare two delay vector distributions. A null hypothesis is assumed in the test which declares that the two distributions are identical and a parameter named as S is calculated using following equation:

\[ S = \frac{\hat{Q}}{\sqrt{V_c(\hat{Q})}} \]  

where \(\hat{Q}\) is the unbiased estimator of squared distance of two delay vector distributions in the state space and \(V_c(\hat{Q})\) is the variance of \(\hat{Q}\). The “S” is a random variable with mean value of zero and standard deviation of 1 under the null hypothesis that the two set of the probability distributions are similar. 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.

By assuming that the time-delayed attractors are similar to delay vector distributions, Van Ommen et al. applied this test to detect changes 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, the attractor of a system can be reconstructed using only a smoothed single measured variable of the system. This can be achieved by applying time delay embedding theory on measured values. Van Ommen et al. recommended using an embedding technique in which the delay vectors are constructed as following:

\[ \tilde{X}_i = x_{(i-1)m+1}, x_{(i-1)m+2}, \ldots, x_{im} \]  

This technique significantly increases the speed of the test due to reduction of the number of delay vectors by a factor of \(m\). It is very effective in situations where there is large number of measured data points like bed vibration signatures. An advantage of the S-test is that it detects changes in the attractor by observing it as a whole instead of focusing on just one property. This method has the ability to detect any changes which happen in the system such as regime transition due to change in the superficial gas velocity.

For the purpose of this work, the sensitivity of the test to small changes in the superficial gas velocity was reduced by normalizing the time series. Detection of regime transition was performed by comparing the reconstructed attractor of each bed vibration signature with the one obtained from a higher superficial gas velocity. The first one was the reference signature which belongs to the lower superficial gas velocity and the other was the evaluation signature which belongs to the higher superficial gas velocity. Since the test is not sensitive to the small changes in gas superficial velocity, a higher value of S (>3) can be related to change in the macro scale structures of the fluidization; In other words, the large bubbles (macro structures) start to collapse and lose their contribution by further increasing gas velocity when compared to the finer structures of the bed (e.g. clusters and particles). This concept is used to identify bubbling to turbulent regime transition, since the finer structures are dominant in turbulent fluidization.

Parameters selection
The performance of the method depends on three parameters which should be chosen properly: embedding dimension \(m\), bandwidth \(d\) and segment length \(l\). Van Ommen et al. mentioned that the time window (time span from which the elements of the delay vector are selected) is also a parameter to be optimized. In this work, all the data points in the time window were used in order to use all the available information from time series. It does not raise any concern about existence of noise because high frequency noises are omitted using a low-pass filter in advance. Thus, by calculating the embedding dimension, the time window becomes determined.

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. There are various methods for selecting embedding parameters: (i) singular-value decomposition of the sample covariance matrix, (ii) "saturation" with dimension of some system invariant, (iii) the method of false nearest neighbours (iv) the method of true vector fields. These methods are used to reconstruct the attractor of the fluidized bed system from pressure or void fluctuations. The lack of a unique solution is a source of uncertainty in nonlinear study of chaotic behaviour of fluidized bed systems. It is still unclear to know the most efficient method; however the reconstructed attractor should be a reliable representation of the state space of the system. In this work, the method of false nearest neighbours was selected. This method has nearly a simple algorithm. Besides, as mentioned by Abarbanel et al., this method comes from asking, directly from data, the basic question that is addressed in the embedding theorem. They also mentioned that it is a powerful method based on an example.

Next parameter to be set is the segment length which reduces the temporal correlation of the underlying data set. According to Theiler, the pairs of points in the time series measured within a short \( \Delta t \) lead to close points in the state space. In fact, these points are close not because of the attractor geometry, but because they are correlated. Temporal correlations are seen in almost every data set; however, their effect is more severe for high resolution time series. To solve this problem, the pairs of points which are close, not due to the attractor geometry, should be excluded. Thus, the recommendation of Theiler was exploited to determine the value of \( l \).

According to this, the time at which autocorrelation function approaches zero \( \tau_a (2/N)^{2/m} \) can be used as a typical time scale. The bandwidth \( d \) is the last parameter to be determined. As indicated by Diks et al., the power of the test depends on this parameter. They stated that taking a too small value for \( d \) leads to a poor statistics as it can be observed from the behaviour of \( \hat{Q} \) by approaching \( d \) toward zero. Moreover, a large value of \( d \) makes the delay vector distributions indistinguishable. Diks et al. mentioned that there is an optimal value at the trade-off of these two limits which depends on numbers of observations. This parameter is selected in a way to make the test as powerful as possible. This was performed by observing the behaviour of the \( S \) value for some different combinations of time series and picking the value for which the maximum of \( S \) occurs; since this method should give a maximal value of \( S \) (higher than 3) for time series of different hydrodynamic conditions.

**EXPERIMENTS**

The lab-scale gas-solid fluidized bed is made of Plexiglas with 0.15 m internal diameter and 2 m height. A perforated plate containing 435 holes with 7 mm triangle pitch was mounted at the bottom of the bed as the distributor of air. A compressor was used to supply the required air and the flow rate was measured by an orifice meter. A cyclone was placed at the column exit in order to return the entrained solids back to the column. The experiments were carried out using three different mean sizes of sand particles (226, 470 and 700 \( \mu \)m) with density of 2600 kg/m\(^3\). Figure 1 demonstrates the size distribution of the three sands used in this work. The experiments were carried out with static bed height of 0.15 cm and superficial gas velocity between 0.1 m/s to 1.6 m/s. Although the effect of electrostatic charge was not investigated in this work, the bed was grounded through several metal wires to decrease the effect of electrostatic charge.
DJB accelerometers (D.J.B. Instruments (UK), Ltd) with sensitivity of 100 mV/ms$^2$ were used to measure bed vibrations. Measuring probes were mounted on the column at three locations of 5, 10 or 15 cm above the distributor plate. Comparing the results from signatures of different probe locations reveals that, in many experimental conditions, the results from different probe locations are the same. Magnets were used to reduce the sudden fluctuations as much as possible. B&K PULSE (Bruel & Kjaer (B&K) Denmark) system with 3560 type hardware was used for converting analogue signals produced by accelerometers to digital signals. The sampling frequency was set to 65 kHz. Fast Fourier transform of some measured signatures obtained from preliminary experiments revealed that the sampling frequency was high enough to ensure that no information was lost based on the Shanon-Nyquist criterion.

By considering the correlation dimension of some time series obtained from preliminary experiments, the time of measurement was chosen long enough to be a good representation of the hydrodynamics of the bed. Ruelle showed that $d_c \leq 2 \cdot \log_{10} N$, thus, by measuring the correlation dimension using the algorithm proposed by Grassberger and Procaccia for preliminary signatures with different number of data points, adequate time of measurements was found to be 30 sec.

Absolute pressure fluctuations were measured at the same time and elevation of the accelerometers using a piezo-resistive pressure transducer of type SEN-3248(B075) (Kobold Company). Absolute pressure fluctuations were measured for 180 sec. with sampling frequency of 400 Hz.

RESULTS AND DISCUSSION

Preparing set of delay vectors from vibration signature

Before applying the S-statistic method, some modifications were performed on the vibration signature in order to optimize the performance of the test. First, 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.

To reduce sensitivity of the test to the small changes of the superficial gas velocity, the influence of the standard deviation is removed by normalizing the vibration time series as:

![Figure 1. Size distribution of the sands](image-url)
\[
x_i = \frac{a_j - \bar{a}}{\sigma_A}
\]

Figure 2 shows that if the vibration signatures are normalized, the sensitivity of the test to changes in the superficial gas velocity decreases significantly. The results shown in this figure were obtained by comparing six time series of various superficial gas velocities near 0.4 m/s with the time series obtained at 0.4 m/s. It can be seen that the S-values obtained from comparisons of normalized signatures are below 3 up to ±0.15 (m/s) velocity change.

It should be mentioned that the sensitivity reduction is effective when no regime transition occurred. In fact, normalizing the signatures cannot reduce the differences between reconstructed attractors of vibration signatures which were obtained from different regimes, since the structures of the fluidization changes as the regime transition occurs.

**Parameters selection**

Figure 3 shows the histogram of embedding dimension of 30 different signatures which were calculated using false neighbours method. Since the embedding dimension used for attractor reconstruction should be equal or greater than the embedding dimension calculated for time series, thus, the embedding dimension was selected equal to 50 for the S-statistic test.
From the basic mathematics, the autocorrelation function, compares linear dependence of data points of a time series separated by delay (\(\tau\)) to determine when the values of \(x(i)\) and \(x(i+\tau)\) are independent enough of each other to be useful as coordinates in a time delay vector, but not so independent as to have no connection with each other at all. Figure 4 shows the autocorrelation function of a vibration signature versus delay (\(\tau\)). It can be seen that at delays above 98, autocorrelation function is approximately zero, in other words, data points are almost independent when they are separated by delays more than 98 points. Autocorrelation times of some signatures were calculated using autocorrelation function and the value of \(l\) was set to 100 which is larger than all the calculated autocorrelation time of the vibration signatures.

Figure 5 shows the behaviour of S-value versus bandwidth for two different categories of the bed vibration signatures. The upper 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 maximum of the curve occurs. The lower curve was obtained by calculating S-values of the signatures with the same condition. As expected, the curve is below the value 3 regardless of the bandwidth. Thus, by selecting bandwidth equal to 1.1, it is ensured that the S-test results in values below 3 for vibration signatures of the same hydrodynamics and values above 3 for vibration signatures of different hydrodynamics.
Detecting regime transition

Hydrodynamic status of the fluidized bed at each velocity was compared with the one at slightly higher velocity using the S-statistic test for their corresponding vibration signatures. If the S-value is greater than 3, it would be concluded with 95% confidence that a change has occurred in the hydrodynamics of the fluidized bed between these two consequent velocities. Although the test cannot determine the origin of the change, but it is already known that the velocity is the only parameter which has been changed. Thus, the recognized change in the system can be originated from either velocity change without regime transition or regime transition due to velocity change. Because the S-test is insensitive to small velocity change, the recognized change can be related to regime transition.

Figure 6 shows the results obtained from the above mentioned comparison for three types of sands used in this work. Each marker point on the curves represents the S-value calculated for the bed vibration signatures of two consecutive superficial gas velocities (0.1 m/s apart). The curves were obtained by calculating S-values for all pairs of consecutive velocities. In the range where the vibration signatures of two consecutive superficial gas velocities represent different hydrodynamic status, the S-value becomes greater than 3. Since the method is insensitive to the change in the gas velocity for the consecutive velocities used in this work, it can be concluded that the dissimilarity predicted by the S-test arises from the difference in the structures in the bed; hence, it corresponds to start of transition. The S-values remain above 3 as the hydrodynamic structures of the fluidized bed continue to change. Finally, the S-value falls below value 3; this shows that the hydrodynamic of the vibration signatures are identical. For instance, the curve related to the medium sand shows that at low velocities, the comparison between bed vibration signatures of consecutive velocities results in S-values less than 3 which indicates that no change has happened in the hydrodynamics of the fluidized bed. Then, the comparison of two consecutive velocities 1.1 m/s and 1.2 m/s results in the S-value greater than 3, which shows that the structures which exist in the bed are changing. In other words, the large periodic bubbles are destroyed and their energy is transferred to the finer structures (e.g. voids and clusters). On the other hand, the comparison of two consecutive velocities 1.2 m/s and 1.3 m/s results in the S-value less than 3 which means that these velocities belong to a similar hydrodynamics. Thus, the point for which S-value falls below 3 is reported as the transition point of bubbling to turbulent regime (1.2 m/s). Figure 6 also shows that the zone in which the fluidization structures are changing until the regime transition occurs is broader for the small sand than the medium and large sands. This can be related to the size distribution of the sands. This zone is the range of velocities for which S-value is greater than 3. It is shown in figure 1 that the size distribution of the small sand is wider than the two other sands. Therefore, it can be expected that the fluidization structure changes in a wider range of velocities for the small sand which consists of a broad range of particle sizes.
The transition velocities obtained with the above proposed method are compared with those obtained from standard deviation of pressure fluctuations, kurtosis analysis of vibration signatures, and also the correlation of Bi and Grace in Table 1. This table indicates that the transition velocity obtained from the S-statistic method is in good agreement with measured values based on the standard deviation of pressure fluctuations, kurtosis analysis of vibration signatures, and those predicted by correlation of Bi and Grace.

Table 1. Summary of the results obtained from different methods (the velocities in m/s are reported)

<table>
<thead>
<tr>
<th>Particle Size (µm)</th>
<th>Bi and Grace’s Equation\textsuperscript{13}</th>
<th>Standard Deviation of pressure fluctuations (Azizpour et al.\textsuperscript{14})</th>
<th>Kurtosis Analysis of Vibration Signatures (Azizpour et al.\textsuperscript{14})</th>
<th>S-statistic of Vibration Signatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>226</td>
<td>0.93</td>
<td>0.89</td>
<td>0.92</td>
<td>1.0</td>
</tr>
<tr>
<td>470</td>
<td>1.22</td>
<td>1.15</td>
<td>1.24</td>
<td>1.2</td>
</tr>
<tr>
<td>700</td>
<td>1.41</td>
<td>1.34</td>
<td>1.37</td>
<td>1.4</td>
</tr>
</tbody>
</table>

CONCLUSIONS

A new approach is proposed to determine the transition from bubbling to turbulent fluidization. The approach utilizes a method named as S-statistic for chaotic comparison of vibration signatures measured in a lab-scale fluidized bed. The S-test can determine whether the vibration signatures are originated from similar hydrodynamics or not. The results of comparisons between vibration signatures of consecutive superficial gas velocities were used to determine points in which structure of the fluidization changes. Since the structure of bubbling regime is different to turbulent regime, detected changes in structures of fluidization can be related to regime transition. The transition point obtained from this approach was compared to those reported in the literature and the close agreement was found. Therefore, the proposed approach is a reliable chaotic analysis in detecting changes in the structure of fluidization.
REFERENCES