An improved wavelet analytical method for studying particle dynamics of the passive layer within a granular drum

Shihang Mou¹, HuiYang¹*, Ran Li¹, Bide Wang¹, Qicheng Sun², Ping Kong³⁴*

¹School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai, China
²State Key Laboratory of Hydrosience and Engineering, Tsinghua University, Beijing, China
³Shanghai Key Laboratory for Molecular Imaging, Shanghai University of Medicine and Health Sciences, Shanghai 201318, China
⁴Department of Science and Liberal Art, Shanghai University of Medicine and Health Sciences, Shanghai 201318, China

* Contact Email: kongp@sumhs.edu.cn; yanghui@usse.edu.cn

Abstract. In this study, conventional threshold way has many defects, for example, the way of extraction of signal processing for the $\delta^2 \mathbf{v}$ and experimental statistics depend on several subjective criteria during the analysis process. Therefore, we introduce another new way of using wavelet analysis that can be extracted valid signals from noise. The results of experiment indicate that it can distinguish noise from the signal $\delta^2 \mathbf{v}$. Compared with the conventional way, the new method has better statistical distribution map of the $\delta^2 \mathbf{v}$ and smaller error.

1. Introduction

The Speckle Visibility Spectroscopy (SVS) method is based on the theory of diffusion wave spectroscopy (DWS) and is a new method for studying time-varying dynamics [1]. This method effectively solves the problem that the DWS method is not applicable to non-stationary stochastic processes. Particles are the most common substance in nature, particles can be divided into regular particles and irregular particles, in life, we can find irregularly shaped particles everywhere, and regular particles are usually made by people. The regular particle motion state in the drum is divided into sliding, collapse, rolling, parabolic motion and centrifugal motion, among them, the collapse mode of particulate matter can be further divided into intermittent collapse motion and continuous collapse motion. Boateng et al [2] divided the bed of particles in the drum into two distinct regions. The two regions are respectively a relatively thin active (or avalanche) layer in the upper part of the bed and a thick passive layer near the rotary kiln wall [1]. Boateng et al [2] supposed that the velocity vectors in the active layer are parallel to the bed surface and vary in a parabolic way, while they change in a linear manner in the passive layer [2,3]. Due to lack of effective methods to measure the tiny displacement of the grain in the drum [1], the passive layer is rarely noticed.

Our research team has done a lot of research about particle dynamics in the drum [4,5,6] for many years. The conventional threshold way used to obtain $\delta^2 \mathbf{v}$ which can’t meet the demands of the
experiment, because the method is simply smooth. However, the smoothing coefficient is determined by people, so there are many problems. The conventional method produces a large error in the whole signal, and many small $\langle \delta v^2 \rangle$ are omitted at the bottom. Therefore, the conventional threshold method has a great influence on small events. Based on the all above, we propose a new method based on wavelet analysis of the phenomenon of passive layer $\langle \delta v^2 \rangle$ in the continuous flow state in the rotating drum [7].

2. Method details

2.1. Instrument and Experimental system design

In Fig.1, there is a experimental device. The inner diameter of the transparent glass cylinder is 150mm, and the distance from the upper bottom to the lower bottom is 200mm, the movement is driven by four drive wheels that are fixed to the roller on the base. RGB designed the DC motor, the reducer are used to drive the drum to rotate at a certain speed through a closed-loop control motor, the laser transmitter NovaProDPSS ($\lambda=532\mu$m, $P = 300$mW). The incident light is diffused through the concave lens and incident on the particles of the active layer in the drum, and the other incident light is directly incident on the passive layer of the particulate matter through the concave lens, that is, the $y$-axis direction is downward in the figure, just like Fig.1(a); DALSA designed the CCD camera with a pixel of 1024, a single pixel length of 14 nm, and a max line speed of 68 kHz. In order to remove the stray light from the surrounding, the CCD surface has a $\lambda$ of 0.532 mm filter. The Fig. 1(b) is a passive layer coordinate system in the our experiment. In the middle is zero position, a spherical particle size of 0.5 mm and a filling degree of 45%.

![Fig. 1. (a) Experimental device. (b) Coordinate side view.](image_url)

The points A0 (x=0mm,y=0mm), A1(x=-6cm ,y=1cm), A2(x=6cm ,y=1cm), A3(x=-5cm,y=2cm), A4(x=5cm ,y=2cm), where, the direction of A1 to A2 is the point of analysis (one point is gauged every 1cm), the point A2 is gauged along the direction, and then gauged in the direction of A3 to A4 along the y direction (every 1cm) to this repeated measurement of point A5(x=0cm,y=7cm) is the bottom of the drum.

2.2. Double Speckle-Visibility Spectroscopy

As shown in Fig. 2(a), scattered light will be shined onto the particulate matter at an intense level when the particles are in the absence of any relative motion. What’s more, speckle will be detected in each pixel. However, when it moves, it will cause the scattered light to fluctuate on the pixel over time just like the Fig. 2(b). During the exposure time, the faster the particulate matter moves, the more blurred the resulting speckle image, lower contrast. Therefore, it can be concluded that random fluctuations between particulate matter will change rapidly with time, for example, the phenomenon of collapse during the movement of particulate matter leads to speckle image changes in Fig. 2(c). Based on the statistical optics theory, the transformation of contrast of speckle image can be indicated by the change of the intensity of light [8, 9].

$$ V_s(T) \propto \langle I^2 \rangle_T - \langle I \rangle^2 \tag{1} $$
Where, the signal $<...>_T$ stands for the average mean value in the duration $T$, $I$ is the scattered light intensity, and $<I>_T$ is the average value of the light intensity in the exposure time $T$. $V_1(2T)$ proportionality constant is determined by the intensity of the laser and the ratio of speckle to pixel size. We can superimpose every 2 sets of data in the original data and get a speckle image at 2x exposure time to eliminate the coherence factor of the system. Then, we get 2 times exposure time $V_1(2T)$ by the same way. Finally, we divide the two sets of contrasts to reduce the coherence factor of the system, ie $V_2(T) = V_1(2T) / V_2(T)$ [8]. Based on the SVS theory [10], we do some research about the reflected light of randomly moving particles. We can get the variance ratio of (d) in the figure by using the following formula:

$$V_2(2T) / V_1(T) = \frac{e^{-\Delta T} - 1 + 4\Gamma T}{4(e^{-2\Delta T} - 1 + 2\Gamma T)}$$  \hspace{1cm} (2)

$\Gamma = 4\pi\delta v / \lambda \Gamma$. The root means square fluctuation of the particles, $<\delta v^2>$, which is equal to the collision velocity and directly related to the so-called granular temperature, which can be achieved by the above Eq. (2), as shown in Fig. 2(e). Then, the $<\delta v^2>$ of the particulate matter can be measured by a certain experimental device, which is decided by the wavelength of the light used and the scanning speed of the CCD camera. Then the method can be used to study the phenomenon which is relevant to the movement of particulate matter in the drum.

![Fig.2. Results and analysis example of SVS with particle point S1 in the drum: (a) intensity across the CCD pixels and time when the drum is stationary; (b) intensity across the CCD pixels and time when the drum is rotating at a speed of 0.23 rpm and no avalanche event occurs; (c) the same as (b) except an avalanche event has occurred in the period of around 0.25-1.25s; (d) intensity variance ratio, Eq. (1), assessed from the data in (c); and (e) indicate particle fluctuation velocity, $<\delta v^2>$, achieved from variance ratio.](image_url)

We pre-process the two CCD to realize the simultaneous measurement of two CCD. First, we put the two CCD together, and the experimental data of 40s is measured. Then, we connect the CCD to the computer, and the laser is illuminated at the same point. Moreover, we get the $<\delta v^2>$ map by the MATLAB software. Finally, we eliminate the time difference between the two CCD by computing the two SVS signal cross-correlation functions.

2.3. Wavelet of the analytical method
It is easy to distinguish because of large pulse changes in the passive layer. Conventional methods do little effect on it, and their statistics do not change, however, when there are many smaller \(< \delta v^2 >\) appear, because the passive layer \(< \delta v^2 >\) value is generally small, and these data contain more useful information, but which of these parameters are useful data, which of these parameters are useless data, we don’t know that how to distinguish real \(< \delta v^2 >\) signal. It will miss many such useful small \(< \delta v^2 >\) pulse data by means of conventional methods. There is no exact calculation formula to get \(\tau\) by using the conventional method. It ignored many small events, and with many personal subjective factors, therefore, conventional methods have a greater effect small \(< \delta v^2 >\), also the \(< \delta v^2 >\) data is not accurate enough. These defects make a good distinction between signals that are useful and those that are not. Giving the conventional threshold formula:

\[
\tau = \left( \sum_{t_1}^{10} \delta \right) / k \quad k=21, 22, 23, \ldots
\]  

(3)

Wavelet transform has been widely employed in computer science signal processing. It can be used to analyze the singularity of different signals. As signals we get in the actual application process are almost discrete data signals, so this paper will adopt the wavelet analysis to deal with \(< \delta v^2 >\) signal. Then we use the library function WNOISEST to extract the detail coefficients of the first layer to compute the standard deviation of the noise signal which is directly related to the threshold, so we gauge the actual noise standard deviation. Finally, compute the \(\tau\) according to the formula:

\[
\left( \frac{\tau}{\sigma} \right)^2 = 2 \cdot \log(N)
\]  

(4)

\(\tau\) is the final threshold, \(\sigma\) is the standard deviation, and \(N\) is the length of the signal\(N=2*10^7\)[7].

Algorithm steps for processing particle temperature by wavelet analysis:

- **Step 1** Disintegrating the \(< \delta v^2 >\) data signal by a one-dimensional wavelet. The \(< \delta v^2 >\) signal with a noisy signal is expressed as \(x(t) = x_0(t) + n(t)\), \(x(t)\) is the \(< \delta v^2 >\) containing noise, \(x_0(t)\) is the true passive layer \(< \delta v^2 >\), \(n(t)\) is a noise signal, under normal circumstances, \(n(t)\) is a high frequency signal. \(x_0(t)\) is the low-frequency \(< \delta v^2 >\), determines a suitable wavelet basis function and the number of decomposition layers, and finally performs one-dimensional decomposition calculation;

- **Step 2** Smoothing and reducing noise on actual measured \(< \delta v^2 >\) signals by means of wavelet analysis, and set the signal of the low frequency part to 1;

- **Step 3** Reconstructing wavelet to get the \(< \delta v^2 >\) signal which was processed;

- **Step 4** Computing the related threshold value by means of the threshold formula of wavelet analysis, and handle the \(< \delta v^2 >\) signal, keep the big threshold portion, the lower part below the threshold goes to zero, finally compute the average \(< \delta v^2 >\) at this point;

- **Step 5** Handling and analyzing the average \(< \delta v^2 >\) of each point.

### 3. Result and discussion

Giving the \(< \delta v^2 >\) effect distribution signal diagram using two different methods respectively. In Fig. 3, we process the data of \(< \delta v^2 >\) at every point separately, and obtain the original \(< \delta v^2 >\) signal map. We use two different methods to process the data, they are the conventional empirical threshold method and wavelet analysis threshold method. Then, we can get every measurement point
of \( \langle \delta v^2 \rangle \) and a pseudo color map of the \( \langle \delta v^2 \rangle \) data distribution. It shows that the conventional one using Fig. 3(a) obtains a pseudo color map of the variation of the \( \langle \delta v^2 \rangle \) distribution, and finds that the closer to the upper left part of the active layer, the higher the \( \langle \delta v^2 \rangle \) but along the x-axis direction to the bottom \( \langle \delta v^2 \rangle \) is getting lower and lower, at the same time, as the drum becomes deeper and deeper along the y-axis, the \( \langle \delta v^2 \rangle \) becomes smaller and smaller, the change in Fig. 3(b) is the same as above, but the comparison is made from the two figures, at the beginning, Fig. 3(a) the \( \langle \delta v^2 \rangle \) is very high, along the x-axis direction, when the position reaches a certain position, the sudden fluctuation of the \( \langle \delta v^2 \rangle \) is almost zero, rather than evenly decreasing, this is not in line with the usual phenomenon, which is much different from the actual phenomenon movement. From Fig. 3(b), we find that the \( \langle \delta v^2 \rangle \) evenly reduces along the x-axis direction, and the \( \langle \delta v^2 \rangle \) region of each particle is of uniform variation, each region has the same size and the variation is linearly decreasing, so distribution of the spherical \( \langle \delta v^2 \rangle \) is better.

Fig.3. (a) Analysis of pseudo-color images of \( \langle \delta v^2 \rangle \) distribution using conventional methods. (b) Pseudo-color image analysis of \( \langle \delta v^2 \rangle \) distribution using wavelet analysis. The experimental conditions are that the drum speed remains 1rpm but changes each measurement position. Just like the Fig. 3(b), the experimental measurement way, the first line along the x-axis direction, 1 cm from the x-axis, is measured in the direction of A1 to A2 shown in the figure, each point is uniformly selected, and the second line is 2 cm from the x-axis, is gauged in the direction of A3 to A4, reciprocate in turn, and measure the seventh line in total (ie point A5).

4. Conclusion
Compared the wavelet analysis method to conventional threshold method, the former is better. Firstly, we analyse the data in our experiment, and find that it obtains better distribution of \( \langle \delta v^2 \rangle \). Second, the \( \langle \delta v^2 \rangle \) change for wavelet analysis experimental data is linear. Third, the new method can eliminate the influence of active layer particle flow. Finally, the \( \langle \delta v^2 \rangle \) near the boundary line did not abrupt [10], which was consistent with the experimental conclusion. All the above indicates that we can distinguish the discontinuity of the passive layer collapse signal from the detail signal and improve the accuracy of the \( \langle \delta v^2 \rangle \) measurement system.

Acknowledgements
This study has been supported by the National Natural Science Foundation of China (11572201, 11572178, 91634202).

References
[1] Li R, Yang H, Zheng G, Zhang BF, Fei ML, Sun QC. (2016) Double speckle-visibility spectroscopy for the dynamics of a passive layer in a rotating drum. J. Powder
Technology, 295: 167-74.

[2] Boateng AA, Barr PV. (1997) Granular flow behavior in the transverse plane of a partially filled rotating cylinder. J. Fluid Mech, 330: 233-49.

[3] Yin HC, Zhang M, Liu H. (2014) Numerical simulation of three-dimensional unsteady granular flows in rotary kiln. J. Powder Technology, 253: 138-45.

[4] H Yang, Jiang GL, Saw HY, Davies C, Biggs MJ, Zivkovic V. (2016) Granular dynamics of cohesive powders in a rotating drum as revealed by speckle visibility spectroscopy and synchronous measurement of forces due to avalanching. J. Chemical Engineering Science, 02: 023.

[5] H Yang, Zhang BF, Li R, Zheng G, Zivkovic V. (2017) Particle dynamics in avalanche flow of irregular sand particles in the slumping regime of a rotating drum. J. Powder Technology, 311: 439-48.

[6] Lin SH, Yang H, Li R, Zheng G, Zivkovic V. (2018) Velocities of irregular particles in a continuously avalanching surface flow within a rotating drum. J. Powder Technology, 295: 167-174.

[7] Mallat SG, Hwang WL. (1992) Singularity detection and processing with wavelets. J. IEEE Transaction on Information Theory, 38: 617-43.

[8] Yang H, Zhang GH, Wang YJ, Sun QC. (2018) Measurement techniques of grain motion and inter-grain structures in dense granular materials. J. Advances In Mechanics, 48: 201812.

[9] Bandyopadhyay R, Gittings AS, Suh SS, Dixon PK, Duran DJ (2005) Speckle-visibility spectroscopy: A tool to study time-varying dynamics. J. Rev. Sci. Instrum. 76:093110-11.

[10] Mellmann J, Specht E, Liu X. (2010) Prediction of rolling bed motion in rotating cylinders. J. Aiche Journal, 50: 2783-2793.