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Analysis of Pressure Signal in a Gas-Solid Two-Phase flow Based on Discrete Wavelet Transform

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ABSTRACT

The discrete wavelet transform was applied to experimental pressure-time signals in this paper, in order to analyze the characteristics of the gas-solid two-phase flow in both Fourier and physical spaces. From randomlike pressure fluctuations, the fluctuating pressure components due to dispersed suspension flow and dune flow can be extracted over a time-scale plane based on the wavelet multiresolution analysis. It was found that the dominant scale of the heterogeneous suspension flow over the dunes increases along flow direction and reaches 0.017s in the fully developed region of dune flow.

Keywords: Discrete wavelet transform, Gas-solid two-phase flow, Particle flow pattern, Pneumatic conveying, Wavelet multiresolution analysis

1. Introduction

The pneumatic conveying is an important operation in a significant number of industrial processes, such as the transportation of materials from storage areas, in catalytic cracking in the petroleum industry, and in the production of synthetic fuels from coal in energy conversion systems. However, the pneumatic conveying is unsteady and complicated nonlinear dynamics system. A detailed understanding of the behavior of particles is importance for design, optimization and operation of the pneumatic conveying system. The prediction or identification of particle flow patterns is one of the important problems. Usually, the flow pattern maps of pneumatic conveying are based on the visual identification of phase distribution. Although identification of visual flow patterns may be adequate for some cases, in many situations these methods are not applicable or are too subjective. Several other methods have been developed to more objectively identify and interpret flow patterns and transitions of two-phase flow, such as pressure-time signals, root mean square (RMS) of pressure-time series, correlation function, skewness and flatness factor, the power spectral density function (PSD) and probability density function (PDF). These studies have contributed to our understanding of flow patterns and transitions of two-phase flow in statistics, but they are utterly incapable of dealing properly with particle flow patterns that is change over time. Although particle flow patterns may be identified by the observation, the unsteady characteristics of pneumatic conveying that the local scale with respect to space-time changes continuously cannot be qualitatively determined yet.

It is well known that the pressure signals contain sufficient information on peculiar features of flow pattern and unsteady characteristics of pneumatic conveying. However, the traditional techniques lost the information on the time for obtaining statistical characters, and are inadequate for unsteady flow.

In the past decade, there has been a growing interest in the application of wavelet analysis to the fluid mechanics. The wavelet analysis can combine time-space and frequency-space analyses and produce a potentially more revealing picture of time-frequency localization of flow structure. This technique has been proposed to identify multi-scale turbulent structure in terms of time and scale, and provided the potentials extracting new information from the complex turbulent flows (1).

The aim of this paper is to develop an application of wavelet analysis to the pneumatic conveying. The wavelet multiresolution analysis is applied to the experimental data of the pressure-time signal in a horizontal pneumatic conveying for studying the characteristics of the wall pressure fluctuation in both Fourier and physical spaces.

2. Discrete wavelet transform

The discrete wavelet transform is a transformation of information from a fine scale to a coarser scale by extracting information that describes the fine scale variability (the detail coefficients or wavelet coefficients) and the coarser scale smoothness (the smooth coefficients or mother-function coefficients) according to:

$$\{D_j\}=[G]\{S_{j+1}\}\ ;\ \{S_j\}=[H]\{S_{j+1}\}\ , \qquad (1)$$

where *S* represents mother-function coefficients, *D* represents wavelet coefficients, *j* is the wavelet level, and *H* and *G* are the convolution matrices based on the wavelet basis function. High values of *j* signify finer scales of information. The complete wavelet transform is a process that recursively applied Equation (1) from the finest to the coarsest wavelet level (scale). This describes a scale by scale extraction of the variability information at each scale. The mother-function coefficients generated at each scale are used for the extraction in the next coarser scale.

The inverse discrete wavelet transform is similarly implemented via a recursive recombination of the smooth and detail information from the coarsest to finest wavelet level (scale):

$$\{S_{j+1}\}=[H]^T\{S_j\}+[G]^T\{D_j\}, \qquad (2)$$

where H^T and G^T indicate the transpose of *H* and *G* matrices, respectively.

The matrices *H* and *G* are created from the coefficients of the basis functions, and represent the convolution of the basis function with the data. In this study, Daubechies wavelet with orders 20 is used as orthonormal wavelets.

3. Wavelet Multiresolution Analysis

The goal of the wavelet multiresolution analysis is to get a representation of a signal that is written in a parsimonious manner as a sum of its essential components. It is well known that a signal often includes too much information for real time vision processing. Multiresolution algorithm process fewer data by selecting the relevant details that are necessary to perform a particular recognition task. That is, a parsimonious representation of a signal will preserve the interesting features of the original signal, but will express the function in terms of a relatively small set of coefficients. Coarse to fine searches processes first a low-resolution signal and zoom selectively into finer scales information.

In this study, the procedure of this wavelet multiresolution analysis can be summarized in two steps:

(1) Wavelet coefficients of a signal are computed based on the discrete wavelet transform of Eq.(1).
(2) Inverse wavelet transform of Eq.(2) is applied to wavelet coefficients at each wavelet level, and components of signal are obtained at each level or scale.

Of course, a sum of these essential components of signal can recover the original signal.

4. Experimental Apparatus and Procedure

In this study the experimental facility is the pressurized system and is shown schematically in Fig.1. Air from a blower flows through the calibrated nozzle, and picks up the solid materials fed by gravity from the feed tank at the inlet of conveying pipeline. Then, the solids-air mixture enters the conveying pipeline and at the pipeline exit the solids are separated from the solids-air mixture by the separator. The conveying pipeline consisted of a horizontal smooth acrylic tube of 76*mm* inside diameter and about 7500*mm* length.

The airflow rate was measured by the orifice meter, and the fluctuation of solid mass flow rate was measured by a load cell. The fluctuations of static pressure along the pipeline were measured at locations *L*=2*m*, 4*m* and 6*m* from the solid feed point by use of semiconductor pressure transducers, whose frequency response is 800*Hz*. The data length of 8000 points for each test case was utilized to carry the wavelet analysis. Polyethylene pellets of 3.5*mm* and a density of 1210kg/m^3 were used as test solids. The mean air velocity U_a was from 6*m/s* to 28*m/s* and the solid mass flow rate G_s from 0.3*kg/s* to 0.5*kg/s*.

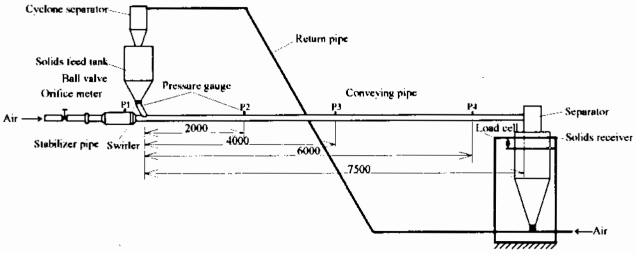

Fig.1 Experimental setup

5. Results and Discussion

In order to reveal features of the pressure fluctuation of the pneumatic conveying in Fourier and time spaces. The wall pressure fluctuation of location x=6m with U_a=18.03m/s and G_s=0.3kg/s, which exhibits the fully suspended flow pattern in the fully developed region, is first analyzed by the wavelet multiresolution analysis. The components of wall pressure fluctuations from wavelet level 1 to 8, which correspond to scale range a=0.01~2.5s, are presented in Fig.3. The time history data of wall pressure fluctuation is also plotted in this figure. This figure represents the time behavior of the fluctuating wall pressure within different scale bands. It is evident that the magnitude of wall pressure fluctuation component increases with decreasing (increasing) the scale (level). The larger alternative positive and negative peaks are observed at level 8, which corresponds to scale a=0.009~0.025s and centers at a=0.017s approximately. The pressure fluctuation component of level 8 represents the fully suspended flow pattern and dominates the characteristics of gas-solid flow. This dominant scale indicates the scale of the dispersed suspension flow. This flow pattern appears to be uniform in the short observation scale.

It is well known that the unsteady characteristics of the flow pneumatic conveying are especially important in the low air velocity range. Next, we discussed transitions of dune flow pattern in the acceleration and fully developed regions.

The components of wall pressure fluctuations for U_a=8.66m/s and G_s=0.3kg/s at locations x=2m from the particle feed point along flow direction ranged from wavelet level 1 to 8, which correspond to scale range a=0.01~2.5s, are shown in Fig.4 (a). The time history data of wall pressure was also plotted in this figure. The obvious nearly periodic large peaks are observed at wavelet level 1, which corresponds to scale a=1.7~2.5s and centers at a=2.1s approximately. These peaks imply the occurrence of the dune flow patterns in the acceleration region, and the scale range is dynamically quite important and dominates the character of flow. The positive peaks represent the passing dune at this moment, and the negative peaks indicate the interval between two successive dunes. The larger amplitude of positive peaks implies a larger dune. The fluctuating pressure components due to dune flow can be extracted from original pressure signal based on the wavelet multiresolution analysis.

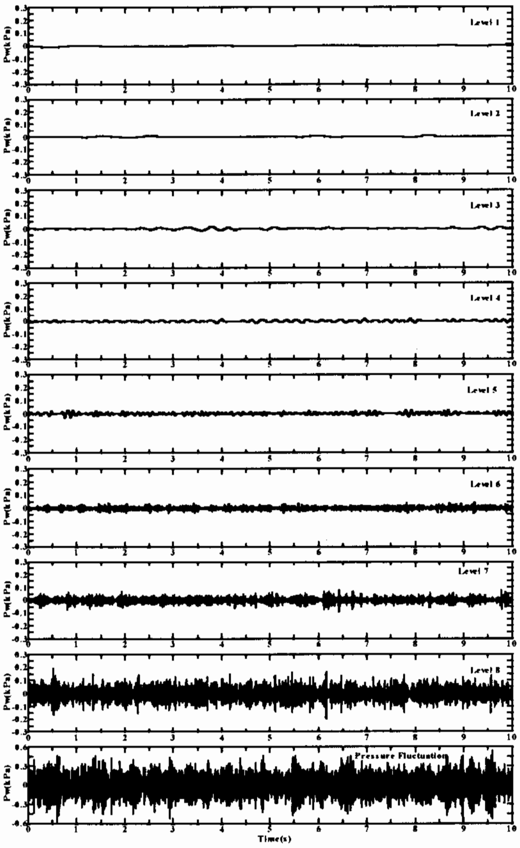

Fig.3 Multiresolution decomposition of fluctuating pressure at location x=6m (U_a=18.03m/s, G_s=0.3kg/s)

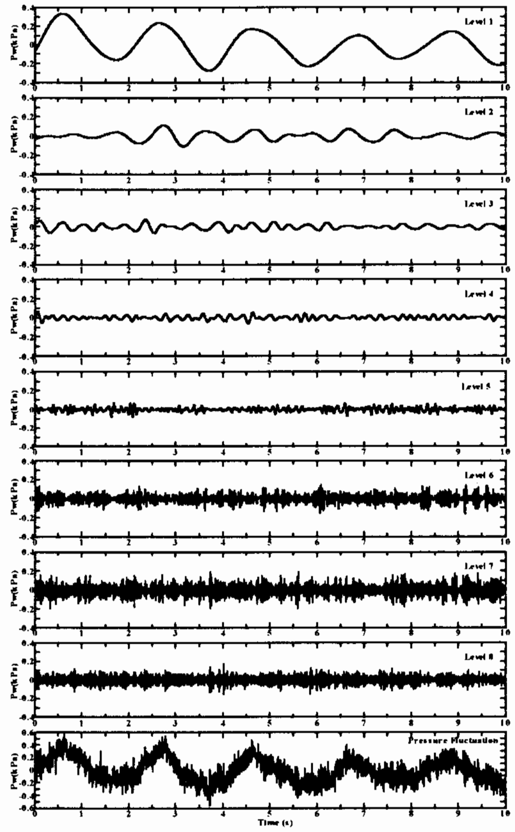

Fig.4(a) Multiresolution decomposition of fluctuating pressure at location x=2m

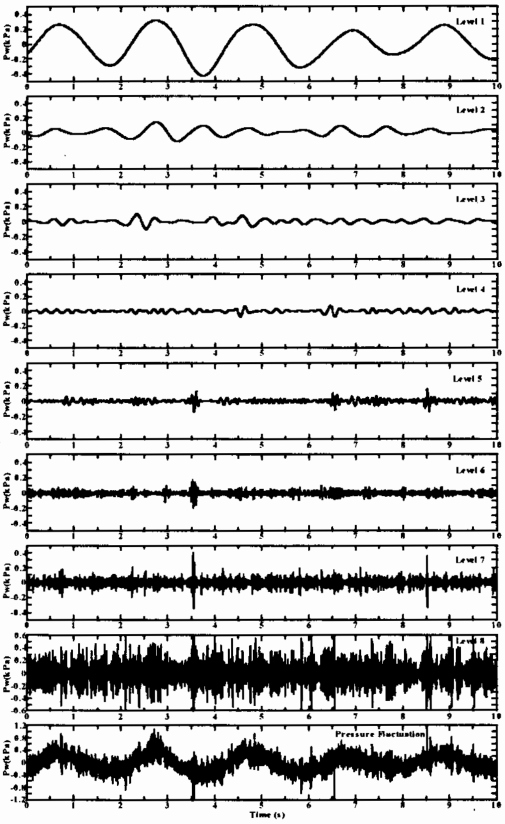

Fig.4(b) Multiresolution decomposition of fluctuating pressure at location x=4m

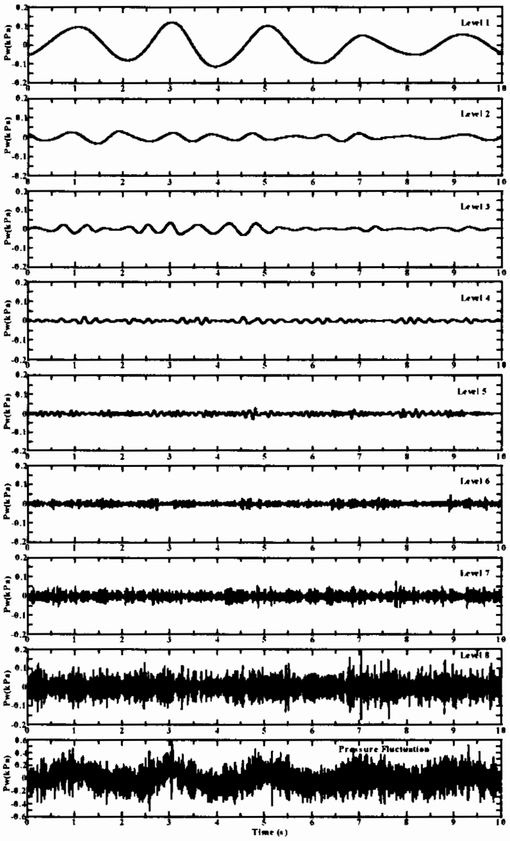

Fig.4(c) Multiresolution decomposition of fluctuating pressure at locations x=6m

Making a comparison between components of wall pressure fluctuations and original wall pressure fluctuation, we find that alternative large positive and negative peaks at level 1 correspond to the positive and negative peaks of the large scale in the original wall pressure fluctuation, respectively. Comparing with other fluctuating pressure components, the larger alternative peaks of the fluctuating pressure component are also observed at level 7, which corresponds to scale a=0.02~0.06s and centers at a=0.03s approximately. These peaks indicate the heterogeneous suspension flow that occupies the rest of pipe over the dunes.

At a downstream distance of x=4m, as shown in Fig.4 (b), the periodic peaks at level 1 that result from the occurrence of the dune flow patterns of are also appeared. The amplitude of positive peaks are almost same, and the flow characteristics may be interpreted the existence of the dunes along the bottom of the pipe at nearly const intervals. Another dominate scale, which results from heterogeneous suspension flow over the dunes, increase and appear at level 8 that corresponds to scale a=0.009~0.025s and centers at a=0.017s approximately, because the particle velocities are accelerated.

In the fully developed region at x=6m, as shown in Fig.4(c), the dominate scales of the dunes and the heterogeneous suspension flow exist at level 1 and 8, respectively, however, the amplitude of peaks decreases. This exhibits that the periodic dune become smaller and the fluctuation of particle velocities in the heterogeneous suspension flow become weaker in the fully developed region.

6. Conclusions

The main conclusions can be summarized as follows:

(1) From randomlike pressure fluctuations, the fluctuating pressure components due to dispersed suspension flow and dune flow can be extracted based on the wavelet multiresolution analysis over a time-scale plane.

(2) For the dune flow pattern, the dominant scale of the heterogeneous suspension flow over the dunes increases along flow direction and reaches 0.017s in the fully developed region.

References

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