ORTHOGONAL WAVELET ANALYSIS OF PARTICLE FLUCTUATION VELOCITY IN A HORIZONTAL GAS-SOLID TWO-PHASE PIPE FLOW AT LOW GAS VELOCITY

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Summary The high-speed particle image velocimetry (PIV) is first used to measure the fluctuating particle velocities in a horizontal gas-solid two-phase pipe flow of low gas velocity. Then the fluctuating particle velocities in the acceleration and fully-developed regimes are analysed by the orthogonal wavelet multi-resolution technique. It is found that the wavelet components of low frequency dominate the fluctuating energy of axial particle velocity in the bottom part of pipe, and contribute about 77% and 86% in the acceleration and fully-developed regimes, respectively. The PDF of low frequency components are asymmetrical near the bottom of pipe, but the PDF of the relatively high frequency exhibits symmetry and the spread of the PDF evidently shrinks for increasing frequencies, implying a reducing fluctuation of high frequency component.

INTRODUCTION

The gas-solid two-phase pipe flow is an important flow phenomenon in a significant number of industrial processes, such as pneumatic conveying of solid particles in pipeline. It is well known fact that the pneumatic conveying of high air velocity causes high energy consumption, pipe erosion and particle degradation. To avoid these troubles the gas-solid two-phase flow is often operated at low gas velocity as soon as possible. However, this operation results in unstable gas-solid two-phase flows and blockage easily. Therefore the optimized design criterion of pneumatic conveying system is to keep the minimum conveying velocity necessary to perform the steady and continuous transport of solid particles. To realize the purpose, it is necessary to reveal the mechanism of gas-solid two-phase flows, especially the dynamics of solid particles in the range of low gas velocity. This is of fundamental significance and has not been previously investigated, thus motivating the present work. Besides a wide range of important applications of gas-solid two-phase flows, there is the strong theoretical interest in explaining the complicated flow phenomena and providing information on behaviours of solid particles for numerical simulation. In this study, the high-speed PIV [1] is first used to measure particle fluctuation velocity in the relatively dense-phase gas-solid two-phase flow. Then the orthogonal wavelet multi-resolution technique [2] is applied to the particle fluctuation velocity, and the multi-scale dynamics of particle fluctuation velocity are analysed in terms of the mean-squared particle fluctuation velocity as well as the probability distribution function at various frequency bands.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup of the gas-solid two-phase flow consists of a transparent smooth acrylic tube with an inside diameter of D = 80 mm and total length of about 5 m. The polyethylene non-spherical particles with a volume equivalent diameter of d_p= 2.3 mm and solid density of 978 kg/m^3 are used as test materials. Here the terminal velocity of the particle is 7.5 m/s. The mean gas velocity U_a and the mass flow rate of solids G_s are respectively fixed at 13.06 m/s and 0.45 kg/s, which is the lowest gas velocity used to stably transport particles without the particles settling on the bottom of pipe. A high-speed camera with a resolution of 1024 X 1024 pixels is used to capture the 2000 successive digital particle images at a frame rate of 1000 fps (frame per second) and the shutter speed of each frame is set at 0.1 ms. A thin light-sheet of thickness = 5 mm is used to illuminate the objective particulate flow on the vertical center plane through the pipe axis. The measurements were carried out at the location of x = 2 m (x/D = 25) and 3.5 m (x/D = 44). In PIV analysis, the interrogation area of 18X25 is adopted in the measurement domain of 80 mm x 111 mm. The statistical uncertainty of the time-averaged axial particle velocity $\bar{u}_p$ is $\pm 4.3\%$ at the 95% confidence level.

RESULTS AND DISCUSSION

Orthogonal wavelet decomposition of mean-squared particle fluctuation velocity

The mean-squared particle fluctuation velocities $\overline{u_p'^2}$ and $\overline{v_p'^2}$ are used to analyse the fluctuating energy of particle velocity in this study. Figure 1(a) shows the normalized profiles of $\overline{u_p'^2}/U_a^2$ versus y/D in the sections of x/D = 25 (acceleration regime) and 44 (fully-developed regime). It is observed that in the top part of pipe $\overline{u_p'^2}/U_a^2$ increase with y/D and maximum value appears near the top of the pipe both for the acceleration and fully-developed regimes. In the bottom part of pipe $\overline{u_p'^2}/U_a^2$ of the fully-developed regime is higher than that of the acceleration regime, implying that the fluctuating energy of axial particle velocity also increases when particles are accelerated.

In order to reveal the intensities of particle fluctuation velocity at various frequency bands, the orthogonal wavelet multi-resolution technique [2] is first applied to decompose particle fluctuation velocity (high-speed PIV data) into eight wavelet levels. Then the time-mean-squared (RMS) particle fluctuation velocity of each wavelet level is calculated by using the wavelet components. To examine the effect of wavelet basis, Daubechies wavelet bases with orders of 4, 8, 10 and 20 are used to decompose the particle fluctuation velocity and calculate the RMS particle

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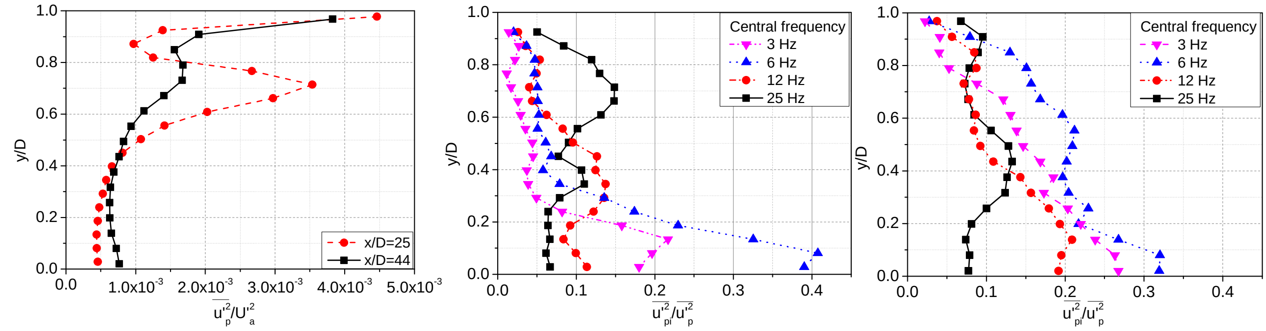
fluctuation velocity of various frequency bands. It is found that RMS of each wavelet level is essentially independent on the choice of wavelet basis having higher than order of 10. Therefore, Daubechies wavelet basis with an order of 10 is adopted in this study.

Figure 1(b) &(c) shows the variation of $\overline{u'^2_{pi}}/\overline{u'^2_p}$ with *y/D* in the central frequency range of 3-25Hz. It is obvious that the maximum value of wavelet components exists near the bottom of pipe and the wavelet component of 6 Hz makes the largest contribution to $\overline{u'^2_p}$ (41% at *x/D* = 25 and 32% at *x/D* = 44). At the location of *x/D* = 25, the wavelet components of 3-25 Hz make the largest contribution to $\overline{u'^2_p}$ around *y/D* = 0.08, accounting for about 77%. When particles are further accelerated and reach the fully-developed regime (*x/D* = 44), the low frequency wavelet components of 3-25Hz account for about 86% around *y/D* = 0.08. However, this contribution decreases with *y/D* and exhibits the minimum value near the top of pipe, accounting for about 11% at *x/D* = 25 and 15.5% at *x/D* = 44. It implies that the contribution from the low frequency component is in direct proportion to the particle concentration.

Probability density function of various frequencies

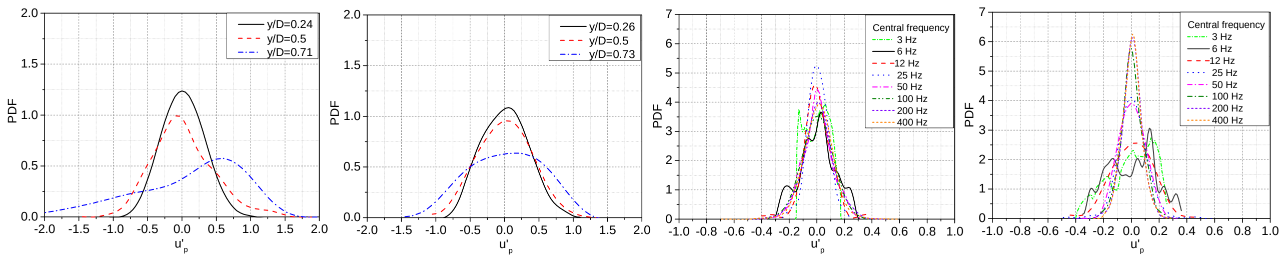
To reveal the characteristics of the relative likelihood of particle fluctuation velocity u'_p and its wavelet components u'_{pi}, the probability density function (PDF) is used in this study. The PDF of the measured u'_p-signals at locations of *x/D* = 25 and 44 for three positions of *y/D* are shown in Fig.2 (a) and (b). The PDF of the measured u'_p-signal displays almost symmetry with respect to $u'_p = 0$ (except the position of *y/D*=0.71), indicating that particle fluctuation velocity follows the Gaussion distribution in the acceleration and fully-developed regimes. At the positions of *y/D* = 0.24 and 0.26, the PDF of *x/D* = 44 spreads more on both sides than that of *x/D* = 25. It implies a larger fluctuating particle velocity in the bottom part of pipe of the fully-developed regime, mainly caused by the particle sliding strands.

The PDF of wavelet components, which are computed based on the particle fluctuation velocity u'_{pi} of various frequency bands, are shown in Fig.2(c) and (d). At the location of *x/D* = 25, the components of PDF having frequencies of 3 and 6 Hz are asymmetrical, the relatively narrow PDF is observed at 3 Hz near the bottom part of pipe. At the location of *x/D* = 44, however, the PDF of less than 6 Hz spreads more on both sides from −0.4 to 0.4 and is significantly asymmetrical with respect to $u'_p = 0$, indicating a larger fluctuating particle velocity of the low frequency caused by the particle sliding strands in the fully-developed regime. The PDF of wavelet component that is higher than 12 Hz at *x/D* = 25 and 44 exhibits almost symmetry with respect to $u'_p = 0$ and the peak of PDF almost increases as the central frequency increases. In the fully-developed regime of *x/D* = 44, the spread of the PDF evidently shrinks for increasing central frequencies, suggesting a reducing fluctuation within a wavelet component of high frequency. However, the slight variation in the spread of the PDF is observed in the acceleration regime of *x/D* = 25. In the range of high frequency (larger than 100Hz), the spread of the PDF in the fully-developed regime becomes smaller than that in the acceleration regime.



(a) Measured data (b) *x/D* = 25 (c) *x/D* = 44

Fig.1 Intensity of particle fluctuation velocity at various central frequencies (U_a=13.06m/s and G_s=0.45 kg/s)



(a) Measured (*x/D* = 25) (b) Measured (*x/D* = 44) (c) *y/D*=0.24 (*x/D* = 25) (d) *y/D*=0.26 (*x/D* = 44)

Fig.2 Probability density function at various central frequencies (U_a=13.06m/s and G_s=0.45 kg/s)

References

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