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Triangle cylinder wake analysis based on wavelet and POD techniques

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Abstract

The turbulent structure behind a two-dimensional symmetric triangle cylinder is measured by PIV experiment at Reynolds number of 14440. To reveal the possibly existed flow phenomena that buried in the mean flow, one dimensional orthogonal wavelet and POD analyses are employed to decompose the fluctuating velocity field into different wavelet components and modes. The features of reconstructed flow fields are analyzed in terms of fluctuating energy, time frequency distribution and length scale. It is found that the first two wavelet components and POD modes can give representations to the most energetic large scale structures, contributing about 77% and 73% to the total fluctuating energy respectively. Comparing with the first two wavelet components, the first two POD modes are more appropriate to represent the Karman like vortical structures. The time-frequency and length scale characteristics of wavelet components suggest that frequency behavior can reflect the spatial related length scale and the wavelet analysis can be used to extract turbulent structures of different scales.

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Keywords: Wake; Wavelet analysis; POD; Turbulent structure; PIV.

1. Introduction

The wake formed behind bluff body is random in time and space domain, exhibiting complex structures with a wide range of coexisting scales. A typical characteristic of cylinder wake is the quasi periodical flow that attributed to large-scale vortex shedding behavior [1], which is found to be a function of velocity, cylinder diameter and Reynolds number [2]. However, besides the large scale structures, it was proved that the turbulent structures of wake consist of a wide range of relatively small scales, such as the secondary vortices [3], Kelvin–Helmholtz vortices [4]

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and longitudinal rib-like structures [5], which may also be of significance in the wake. In order to give a detailed description of wake flow structures, the identification of the energetic large scale structures and elucidation of relatively small scale structures is very desirable, and the emergence of wavelet and POD analysis provide particularly powerful tools.

During the past decades, many researchers have made use of the wavelet transform method to provide both the spectral and temporal (or spatial) information of turbulent wake flows. As an example, Rinoshika and Zhou [6] have applied the one-dimensional orthogonal wavelet multi-resolution technique to the analysis of the cylinder wakes, by which turbulent structure were decomposed into a number of wavelet components based on their characteristic or central frequencies. However, to give further understanding of turbulent wake, the decomposed wavelet components can be further investigated in terms of statistical parameters such as fluctuating energy, turbulent spatial scale and Reynolds correlation functions, which will provide new insights into the multi-scale structures of turbulent wake.

The other popular technique used to detect and extract different dynamic behaviors presented in a flow is the proper orthogonal decomposition technique (POD). Since the pioneer work of Lumley [7], POD analysis has been widely used to extract coherent structure [8]. Since the wavelet analysis can also be used to extract large-scale turbulent structures characterized by its central frequency. The large-scale structures extracted by these two approaches may have different physical properties due to the different classification criterions of them. This will be of interest and has not been previously investigated, thus motivating the present work.

In this study, the high-speed PIV was applied to measure turbulent wakes generated by a triangle cylinder in the circulating water channel. In order to reveal the possibly existed flow phenomena that buried in the mean flow, we applied one dimensional orthogonal wavelet and POD analyses to decompose the fluctuating velocity field into different wavelet components and modes. The features of reconstructed flow fields are analyzed in terms of fluctuating energy, time frequency distribution and length scale.

2. Experimental setup

As shown in Fig.1, a two-dimensional symmetric triangle cylinder model, having a scale of L = 50 mm and aspect ratio of 8 with respect to its whole length, was adopted in this study. The high-speed PIV measurements was carried out at a constant free stream velocity of U_0 = 0.29 m/s, which corresponds to Reynolds number of 14440. Polystyrene particles with a diameter of 63μm were seeded in the flow loop as PIV tracers. A high-speed camera (Photron FASTCAM-MAX I2) and a laser light sheet were used to capture the digital images at a frame rate of 500 fps (frame per second) with a resolution of 1024×1024 pixels and the shutter speed of each frame was set at 1 ms. 15000 instantaneous velocity fields were analyzed by ProVision PIV software.

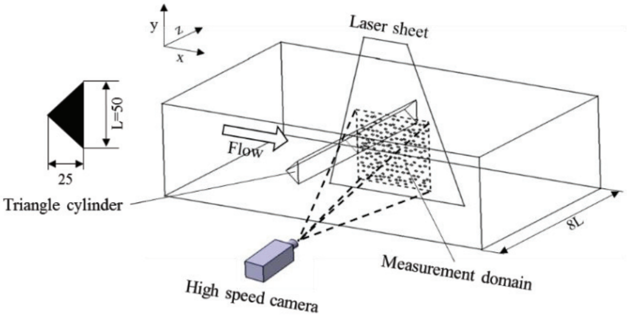

Fig.1 Experimental model and measurement setup

3. Decomposition of velocity field

Before the decomposition, the sequential realizations of velocity field were selected to calculate the fluctuating velocities by subtracting the mean velocity field. The calculation was given by:

$$v'(x_i, y_j, n) = v(x_i, y_j, n) - \overline{v(x_i, y_j)}\ ,\ i=1,\ \dots,\ n_x;\ j=1,\ \dots,\ n_y;\ n=1,\ \dots,\ n_t. \qquad (1)$$

Here the v denotes streamwise (U) or vertical velocity component (V), the x_i and y_j represents the local spatial positions and the n is the time sequence of snapshot. Then one dimensional orthogonal wavelet [6] and POD [9] approaches were employed to decompose the resulting fluctuating velocities into different wavelet components and POD modes.

4. Results and discussion

4.1. Energy distribution of wavelet components and POD modes

As shown in Fig.2a, the first four wavelet components contain 88% of the total kinetic energy, and the wavelet components of level 1 and level 2 makes the largest contribution, accounting for 32% and 45% respectively. It indicates that first two levels of wavelet components can be associated with the large scale turbulent structure, which is apparently the uppermost and energy-containing structure. Fig.2b presents the energy distribution of first 50 POD modes (about 2.5% of the total POD modes), as expected, the first two POD modes are most energetic, containing 73% of the total kinetic energy (first and second modes contribute 41% and 32%, respectively), however, the energy content of mode 3 and 4 reduce rapidly to 2.8% and 2.1%, and the rest of modes make less contributions with increasing mode number. The energy concentration on first two modes suggests that the vortex shedding process can be linked to the first two modes.

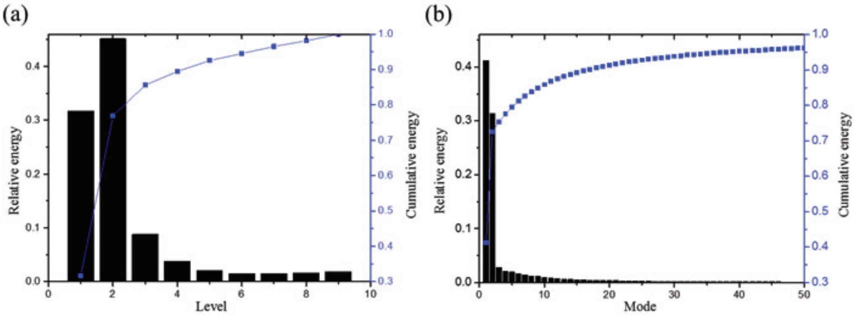

Fig.2 Energy distribution (a) distribution of wavelet components (b) distribution of POD modes

4.2. Time-frequency analysis

In order to reveal frequency behavior of the possibly existed flow phenomena, continuous wavelet transform was applied to the wavelet components and POD modes of vertical velocity at a selected point (x/L=1.2, y/L=0.48). Figure 3 shows time frequency distributions of first four levels of wavelet components. It can be seen that the dominating frequency increases with increasing level number, the corresponding Strouhal number are observed at st ≈0.17, 0.2, 0.42, and 0.8 by level 1, 2, 3 and 4, respectively. On the contrary, the fluctuating energy of last three wavelet components (level 2-level 4), which can be described by the coefficients of continuous wavelet transform, decrease as increasing frequency. It implies that the frequency behavior of fluctuating velocity is dominated by wavelet components of low frequency, which can be associated with the dynamics of large scale vortices. The wavelet components of relatively high frequency indicate that the wavelet components of level 3 and 4 can be linked to small scale structures. The time frequency distributions of first four POD mode is shown in Fig.4. It is observed that the first two modes (Fig.4a and 4b) are most energetic, having strong quasi periodical characteristics at a corresponding Strouhal number of 0.21. This confirms that the first two modes are related to the fundamental frequency of vortex shedding and they are able to give representations of the dominant Karman like vortices. Considering the higher POD modes, Figs 4c-4d do not exhibit evident periodical behaviors, the corresponding Strouhal numbers are observed in a wider range, the higher frequency components (St=0.35-0.75) may associate with small scale eddies. The lower frequency components (St=0.08-0.13) may be due to unsteady flow motion induced by Karman like vortex shedding behavior [10], and they are not the dominant structures.

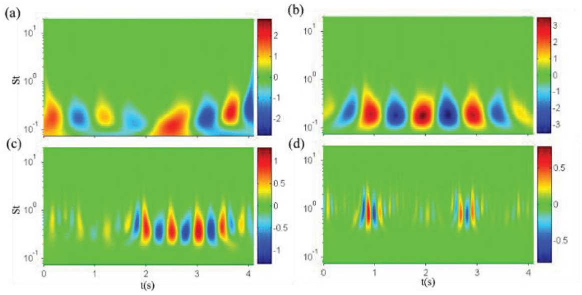

Fig.3 Continuous wavelet transform of wavelet components at x/L=1.2, y/L=0.48 (a) Level 1 (b) Level 2 (c) Level 3 (d) Level 4.

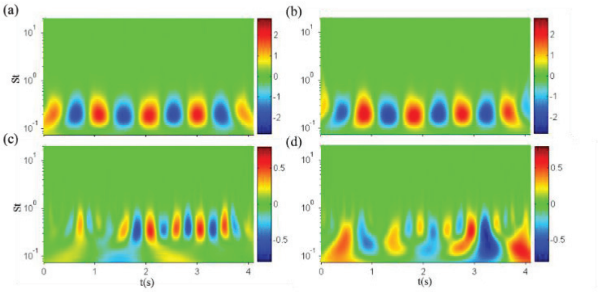

Fig.4 Continuous wavelet transform of POD modes at x/L=1.2, y/L=0.48 (a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

4.3. Scale characteristics of wavelet components and POD modes

In order to determine the scale length of them, we computed two-point autocorrelation function for each wavelet component and POD mode. Figure 5 presents correlation function of wavelet components and POD modes at the location of y/L=0 along the streamwise direction. From Fig.5a, it is evident that all the coefficients reduce to theirs first minimums and continue oscillating before they become zero at about x/L=2.8, the length scales of x/L =2.2, 2.0, 0.9, 0.75, 0.5 and 0.36 are observed by wavelet components from level 1 to level 6 respectively, and the length scale decreases with increasing frequency. The first two wavelet components can give representation of large scale structures, wavelet components of level 3 and 4 can be regarded as relatively small scale structures, and the wavelet components of level 5 and 6 may contain some random and noisy events. These observations may indicate that multi scale vortical structures are organized by the components characterized by their dominant frequencies. The length scales of first two wavelet components confirm the fact that low frequency components are associated with large scale vortical structures， and the larger length scale of first wavelet component may suggest that the unsteady flow motion induced by Karman like vortex shedding behavior results in the generation of relatively larger vortical structures. The scale characteristics of wavelet components suggest that the frequency behavior can reflect the spatial related length scale of vortical structure and the wavelet analysis provides a tool for extracting vortical structures of different scale. The coefficients of POD modes is shown in Fig.5b, the length scales of first two POD modes are nearly the same with the value of x/L 2.1, indicating the length scale of Karman like large scale vortical structure. As for higher POD modes, the length scale of x/L =1.15, 1.75, 0.85 and 1.3 are observed by POD mode 3, 4, 5 and 6 respectively. Different with wavelet components, no evident relationship between POD mode and length scale can be found, this is because wider range of frequency contained in POD modes. Concerning the result of POD analysis, the first two modes give a good representation of Karman like vortical structure due to the frequency and length scale characteristics of them, however, it is difficult to extract small scale vortical structures as the fluctuation velocity components are irregularly classified in frequency and spatial domain.

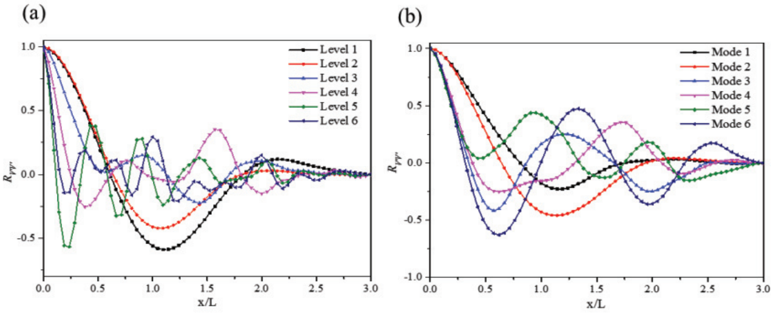

Fig.5 Distributions of two-point autocorrelation coefficients (a) Wavelet components (b) POD modes

5. Conclusion

The turbulent structures behind a two-dimensional symmetric triangle cylinder are measured by PIV experiment at Reynolds number of 14440. One dimensional orthogonal wavelet and POD analysis are employed to extract possibly existed flow phenomena that buried in the mean flow. The features of reconstructed flow fields are analyzed in terms of fluctuating energy, time frequency distribution and length scale. The following conclusions can be drawn.

1. The first two wavelet components and POD modes are most energetic, contributing about 77% and 73% to the total fluctuating energy respectively. The energy distributions of them indicate that they are capable of extracting dominating large scale turbulent structures.

2. Compared with POD modes, the central frequencies of wavelet components is distinctly classified as the band pass filter process of orthogonal wavelet analysis. The time-frequency analyses suggest that the first two POD modes are more appropriate to represent the Karman like vortical structures due to theirs strong quasi periodical behaviors at St=0.21. When increasing to higher modes, poor filtering effects in the range of lower frequency (St=0.08-0.13) is observed, and the lower frequency components are considered to be superimposed on the wavelet component of level 1. This can be interfered as a reason why the energy content of first two wavelet components is larger than that of first two POD modes.

3. The length scale of wavelet components is found to decrease with the increasing frequency, suggesting that the frequency behavior can reflect the spatial related length scale and the wavelet analysis can be used to extract turbulent structures of different scales.

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