THREE DIMENSIONAL NUMERICAL INVESTIGATIONS OF WIND ENVIRONMENT AROUND LANQIYING BUILDINGS

Chen Jianguo[1,2], Liu Yi[1,2], Yang Rui[1,2], Shen Shifei[1,2]

[1] Center for Public Safety Research, Tsinghua University, Beijing, 100084, China
[2] Department of Engineering Physics, Tsinghua University, Beijing, 100084, China

ABSTRACT

The three-dimensional wind environment in Lanqiying community of Beijing city, which is complicated due to the dense distribution of the high-rise buildings, is investigated by computational fluid dynamics method. The turbulent flow past the buildings is simulated by solving the incompressible Reynolds-averaged Navier-Stokes equations. Both the reverse flow between the buildings and the recirculation of the wake can be observed. The spectrum analysis of aerodynamics coefficient are successfully obtained and compared with the two-dimensional results. The vortex interactions with each other result in different characteristic frequencies and power values, corresponding to various-scale vortex shedding behind the buildings.

KEYWORDS

High-rise building group, Vortex shedding, Wind environment

INTRODUCTION

With the rapid increase of high-rise building groups in recent years, much attention has been given to the influence of wind environment around the apartment block on life quality. Generally the design of building groups only considers the wind load effect disregarding the aerodynamic characteristics of wind (Su and Tang 1996, Song and He 1993). However, the wind flow and the buildings will interact with each other under certain wind speed, leading to the flow separation, vortex shedding and vortex-induced vibration (Song and He 1993, Murakami et al. 1990, Ping et al. 1997), which would be of negative effect on the safety of building structures. For instance, raise of dust and garbage, transfer of grimy gases, and the changed distributions of wind pressure and load on the building surface with the imposition of wind, may lead to wind-induced vibration, resulting in weary distortion of architectural materials, maladjustment of heating and ventilation system, and locally severe aeolian noise. In Beijing city, spring and winter are much windy seasons, and the maximum wind power may reach to above Force Seven (>15 m/s), so that it is necessary to deeply analyze the evident interaction of high-rise building groups with wind environment.

The wind environment in Lanqiying community of Beijing city, which is complicated due to the dense distribution of the high-rise buildings, is investigated by the computational fluid dynamics method. We did the primary simulation under two-dimensional assumption (Chen, 2003). However, the numerical investigation should be generalized to three dimensions for clearly understanding the wind environment of this building group. Therefore, the three-dimensional turbulent flow past the buildings is simulated in this paper, by solving the incompressible Reynolds-averaged Navier-Stokes equations and the k-ε two-equation representing the turbulence effect with the application of a finite volume method. The meaningful results of the wind environment and wind load around the Lanqiying building group are successfully obtained and compared with two-dimensional analysis.

NUMERICAL SIMULATION METHOD

Introducing standard k-ε turbulence model, the incompressible unsteady Reynolds-averaged equations can be written as follows in a general form

$$\frac{\partial \phi}{\partial t} + R(\phi) = 0,\quad R(\phi) = \nabla \cdot \left(\bar{\mathbf{V}}\phi\right) - \nabla \cdot \left(\Gamma_\phi \nabla \phi\right) - S_\phi \quad (1)$$

For the continuity equation $\phi = 1$, $\Gamma_\phi = 0$, and $S_\phi = 0$, for the momentum equation $\phi = U_i$, $\Gamma_\phi = \nu_{eff}$ and $S_\phi = -\frac{\partial p_{eff}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu_{eff}\frac{\partial U_i}{\partial x_j}\right)$, for the turbulence kinetic equation $\phi = \mathrm{k}$, $\Gamma_\phi = \nu + \frac{\nu_t}{\sigma_k}$ and $S_\phi = G - \varepsilon$, and for the turbulence dissipation equation $\phi = \varepsilon$, $\Gamma_\phi = \nu + \frac{\nu_t}{\sigma_\varepsilon}$ and $S_\phi = (C_1 G - C_2\varepsilon)\frac{\varepsilon}{k}$, where $\nu_{eff} = \nu + \nu_t = \nu + C_\mu \frac{k^2}{\varepsilon}$, $G = -\overline{u_i u_j}\frac{\partial U_i}{\partial x_j}$, and $\overline{u_i u_j} = \frac{2}{3}\delta_{ij}k - \nu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$. In the model, the constant parameters are usually determined by experiment and numerical optimization procedure as C_μ=0.09, C_1=1.44, C_2=1.92, σ_k =1.0, and σ_ε=1.3 (Jones and Launder 1972).

The equations are solved by using the Finite Volume Method. The convection term in R is discretized by second-order HLPA (Zhu 1991) scheme, and the diffusion and source term by central difference scheme. About the time term, second order TLFL(Three Layer Fully Implicit) scheme (Zhu 1991) is used to discretize the time derivation. For each control volume, the following expression stands

$$\frac{3\phi_{ij}^{n+1} - 4\phi_{ij}^{n} + \phi_{ij}^{n-1}}{2\Delta t} + R_{ij}(\phi^{n+1}) = 0 \qquad (2)$$

Where Δt is the real time step. For equation (2), Strong implicit procedure (SIP) is used to advance the time (Zhu 1991). In every real time step, SIMPLE method is used to solve pressure field. Meantime the momentum interpolation method is applied for avoiding the pressure fluctuation induced by non-staggered grid system.

The inflow wind is along the x-axis with the profile described by (Wang et al. 2004)

$$U_{\infty}(z) = U_{10}\left(\frac{z}{10}\right)^{\alpha} \qquad (3)$$

where U_{10} is the wind speed at 10 m above the ground. In Beijing, the wind prevailingly comes from the north direction, so in the present paper we only consider the north wind. The parameter α is the function of surface roughness and atmospheric stability, typically $\alpha = 0.16$ for rural wind conditions or $\alpha = 0.24$ under the neutral condition in urban boundary layer.

For the boundary conditions, the inlet is the uniform inflow with the atmospheric condition, and the inflow velocity, the turbulence kinetic energy and dissipation rate in the inlet are given by

$$U_{in} = U_{\infty},\ k_{in} = (0.02U_{in})^2,\ \varepsilon_{in} = C_{\mu}k_{in}^{\ 2}/(100\nu) \qquad (4)$$

The properties are fixed constants at the inflow boundary, while in the open-ended boundaries are

$$\frac{\partial u}{\partial x} = 0,\ \frac{\partial v}{\partial x} = 0,\ \frac{\partial k}{\partial x} = 0,\ \frac{\partial \varepsilon}{\partial x} = 0 \qquad (5)$$

The walls of the buildings and the ground surface are assumed to be no-slip, and the wall-function is used to solve near-wall turbulence.

COMPUTATIONAL RESULTS AND ANALYSIS

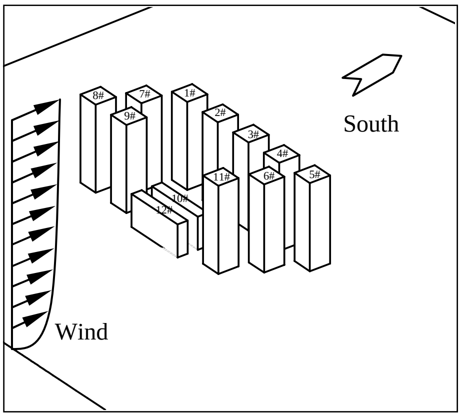
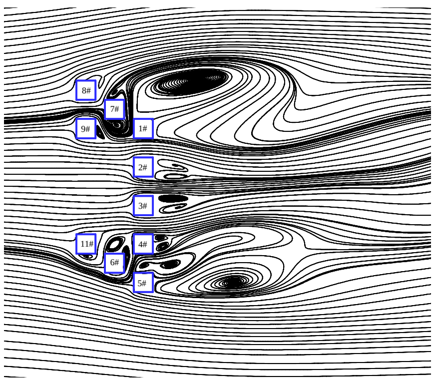
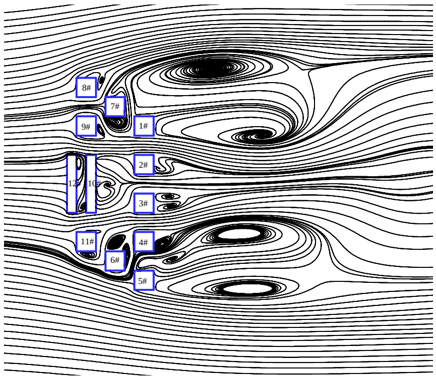


Figure 1 Sketch of building group and wind inflow condition

The Lanqiying community consists of 12 buildings, ten of which are much higher than the surrounding buildings 10# and 12#, as is sketched in figure1. The dimensionless computational domain is 44×41×14 in which the building width is taken as the characteristic length. The total mesh number is 128×120×64 with H type. For the three-dimensional computation, the buildings are simplified as cuboids with dimensions 0.5×3×1.5 (depth by width by height) for 10# and 12# and 1×1×4 for others. In our previous work (Chen et al. 2003), the plane considered is much higher than the ground surface, so that the influence of 10# and 12# buildings on the flow can be neglected and the flow field can be simplified as the two-dimensional domain. The Reynolds number are 2×10^6, with the characteristic length taken as the building width and the characteristic velocity as the Force Seven wind velocity, which are the same as in the previous two-dimensional simulations.



(a)



(b)

Figure 2 A Cross-sectional streamline of (a) z=2 and (b) z=0.75 planes

Figure 2 illustrates the cross-sectional streamline of the flow at z=2 and z=0.75 planes where three-dimensional computations are considered. The flow field typically includes complicated vortex structures, and the plane-by-plane inspection of the flow is one of the effective techniques to depict the flow patterns. Both the reverse flow between the buildings and the recirculation of the wake can be observed in figure 2, where the flow separation occurs in the lee of the buildings and the large-scale vortex structures are generated due to the vortex interactions with each other. The z=0.75 plane is close to the ground surface, and the influence of 10# and 12# buildings on the flow characteristics is evident.

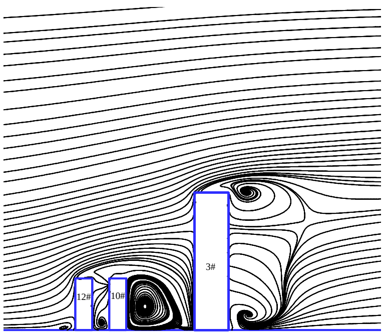


Figure 3 Cross-sectional streamline released from a plane across 10#,12# and 3# buildings along y-axis

For further understand the flow characteristics, the streamline pattern in a streamwise elevation for the symmetry plane across 10#, 12# and 3# buildings is depicted in figure 3. The diagram shows clearly the vertical character of the reverse-vortex which is formed between the buildings, the shear separation from the lee corner of the tall building, and the recirculation of the flow downstream of the buildings. The reverse eddy behind the lee face of 10# building may locally raise the dust and garbage leading to the pollution of the community environment. Therefore, it is of necessity to strengthen the virescence at this region.

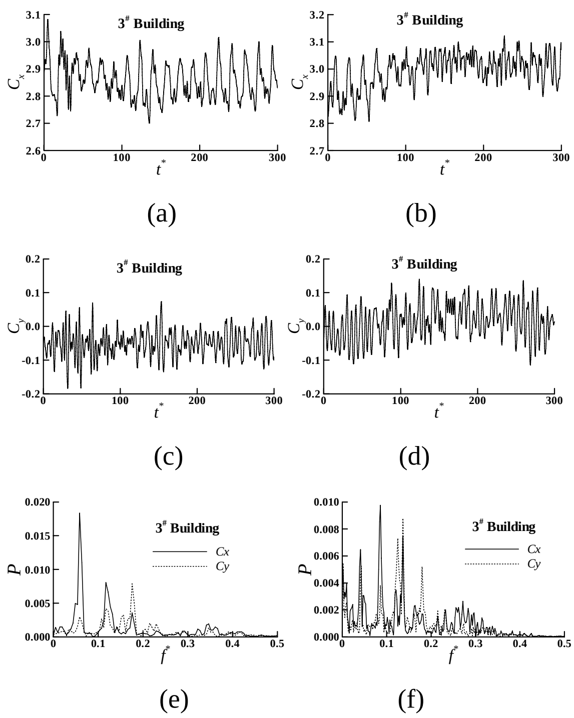


Figure 4 Temporal evolution of aerodynamic coefficients C_x and C_y in x- and y- directions and the corresponding spectrum analyses for 3# building, where (a), (c) and (e) for two dimension and (b), (d) and (f) for three dimension

The aerodynamic coefficients of x- and y-direction, C_x an C_y, are defined as $C_x = F_x/(1/2\rho U_\infty^2 WH)$ and $C_y = F_y/(1/2\rho U_\infty^2 WH)$, of which the temporal evolution and the corresponding spectrum analyses are shown in figure 4 for 3# building and in figure 5 for 11# building. For the convenient comparison of three-dimensional results with the two-dimensional, the two-dimensional results are also given, (a), (c) and (e) in figure 4 and 5 referred from Chen (2003). The unsteady characteristics of the flow field are evident.

The spectrum analysis depicts the dependence between the frequency and the power. It is found from the spectrum analyses of the aerodynamic coefficients that some characteristic frequencies appear. The spectrum includes the basic, diploid, multiple frequencies, and their combined frequencies due to the nonlinear interactions of the buildings with the flow field, illustrating evident turbulent characteristics. Furthermore, in comparing the results of three dimensions with those of two dimensions, for instance (e) and (f) in figure 4, the main characteristic frequencies are 0.051, 0.114 and 0.17 for two dimensions, different from 0.041, 0.086 and 0.136 for three dimensions, due to the different vortex interactions with each other under two- and three-dimensional conditions. The characteristic frequencies are the ones corresponding to various-scale vortex shedding behind the buildings. The three-dimension effect makes the power values lower than the simplified two-dimensional ones. Besides the power values, the leading frequency are also different. As is shown in figure 2 that for 3# building, the large-scale vortex downstream of the building is the main factor affecting the aerodynamic coefficients, while for 11# building the small-scale vortex shedding from the surrounding buildings are dominant.

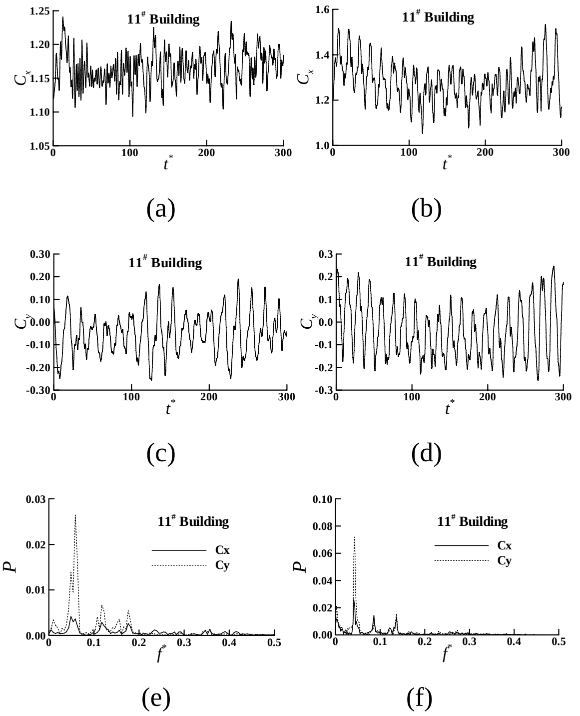


Figure 5 Temporal evolution of aerodynamic coefficients C_x and C_y in x- and y- directions and the corresponding spectrum analyses for 11# building, where (a), (c) and (e) for two-dimensional and (b), (d) and (f) for three-dimensional computations

CONCLUSION

The three-dimensional wind environment of a high-rise building group, Lanqiying community of Beijing city, has been carefully investigated based on the standard k-ε turbulence model. The flow characteristics are given, where the reverse flow between the buildings and the recirculation of the wake can be observed. The spectrum analysis of aerodynamic coefficients depicts the dependence between the frequency and the power. Compared with two-dimensional results, the characteristic frequencies and the power values are different, due to the different vortex interactions with each other. The characteristic frequencies correspond to the various-scale vortex shedding behind the buildings. The results of the numerical simulations provide references for the building designers and residents in the community to understand the influence of wind on the environment and load of these high-rise buildings.

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