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Large-eddy simulations of wind flow passing a building cluster

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SUMMARY:
This paper presents high fidelity large-eddy simulations (LES) of wind flows with different directions passing a cluster of 2×2 aligned square cylinders, of which each has side length of D, at Reynolds number $Re = 22,000$. A so-called 'cluster effect' has been found, in which the vortex structures in the far-field wake are governed by the cluster rather than individual cylinders. Their characteristic length and time scales are close to the cluster size $2D$. The cluster effect increases monotonically as the flow incidence angle increases.

Keywords: LES, building cluster, wake interaction

1. INTRODUCTION

The aerodynamic behaviour and wake flow of a cluster of tall buildings is very complex due to strong interaction in the wake in both near and far fields. Understanding their aerodynamics is limited because of high cost of wind-tunnel experiments and numerical simulations. Using these approaches to study study wake flows of a cluster of tall buildings with Renoylds numbers larger than the critical one (Re $\approx 10^4$) is very challenging. This is because it requires large testing sections and computational domain that available resources are very limited.

Most of past studies (Agrawal et al., 2006; Burattini and Agrawal, 2013; Sau et al., 2007) on flow characteristics passing two side-by-side square cylinders were conducted at low Reynolds numbers (e.g. less than 100). Burattini and Agrawal, 2013 showed that, for Reynolds number equal to 73, the Strouhal number of vortex shedding was almost constant and near 0.16, within a range of spacing $0.5D$ to $6D$, where D is the cylinder side length. A few studies have been conducted for higher Reynolds numbers. Han et al., 2014 studied the wake characteristics of two side-by-side square cylinders at a Reynolds number 22,000. Alam et al., 2011 experimentally investigaged the wake flow of two side-by-side square cylinders at a Reynolds number 47,000 at a centre-to-centre spacing pitch ratio ranging from 1.02 to 6. Based on the authors' knowledge, no study has been reported for the wake of flow passing a cluster of 2-by-2 cylinders. The information of how the dominant vortices are characterised through shedding frequency is lacking.

Starting from those remarks and aiming at shedding some lights on the mechanism of windflow around cylinder clusters with an implication for relevant applications such as tall building cluster, a series of LES for different sets of cluster of square cylinders and tall buildings with different inlet conditions has been conducted by the authors. Some preliminary reasults have been reported in Inam et al. (2022) and C. H. Nguyen, Inam, et al. (2023). This paper presents large-eddy simulations for 2-by-2 square cylinders subjected to different smooth wind directions at the inlet with Reynolds number 22,000.

2. NUMERICAL SETUP

An arrangements of a two by two array of square cylinders, each with a size D, with a centre-centre spacing of $2D$ (see Fig. 1a) were considered. The Reynolds number was $Re = 22,000$ based on the freestream speed U_∞ and the cylinder size D. Five wind directions with angles of attack $\alpha = 0°, 11.25°, 22.5°, 33.75°$ and $45°$ were simulated. Fig. 1a shows the computational domain dimensions and the partition of the structured mesh. The final mesh structure for all considered flow directions was with a fine mesh of 73 million cells, which was validated in C. H. Nguyen, Inam, et al. (2023) . The resolution of the first near wall grid was always equal to $D/200$, equivalent to less than 5 wall units. Fig. 1b shows the locations of the probes to measure the wind velocity fields.

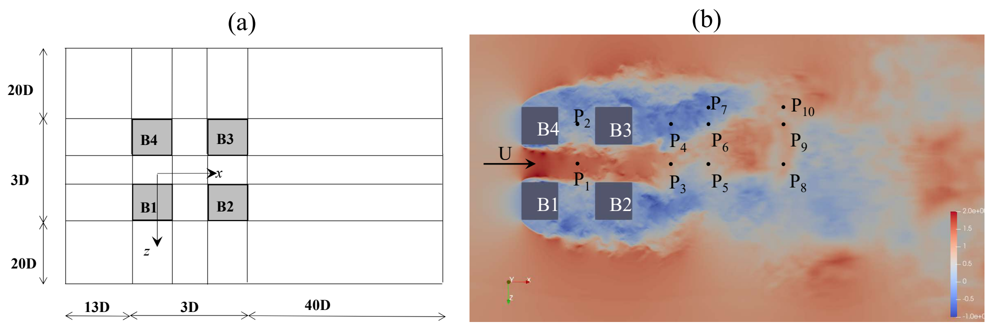

Figure 1. (a) A sketch of the computational domain (not to scale) and its partition for structured mesh; (b) Locations of velocity probes P_i and instantaneous velocity field u_x at $\alpha = 0°$

Uniform velocities were imposed at the inlet (left) and the top boundaries. The outflow boundary condition was imposed at the bottom and outlet (right) boundaries. In the spanwise direction, periodic boundary conditions were used. No-slip boundary condition was applied on the cylinder surfaces. For all simulated cases, the initial duration for LES was more than 150 t^*, the duration for average was more 200 t^*, where $t^* = tU_\infty/D$ is the non-dimensional time. Up to 4096 cores (CPUs) were used for the simulations.

3. RESULTS AND CONCLUSIVE REMARKS

Figure 1b shows a snapshot of the instantaneous velocity u_x for the case $\alpha = 0°$. A strong channelling effect can be seen with separation and reattachment on the inward sides of the front cylinders B1 and B4. This observation is different from the case of flow around an isolated square cylinder where the reattachment does not occur (e.g. Chen et al., 2020). The channeling effect is less appearing as the wind direction is increasing. At the exit of the along-wind spacing, a pulsing jet flow is visible with strong vortices shed in a slightly asymmetric pattern. They are slow and irregular. For higher wind angles, they are faster and more regular.

To quantitatively investigate the characteristics of the flow in the near and far field of the wake, wavelet analysis (e.g. C. H. Nguyen, D. T. Nguyen, et al., 2022) is employed to analyse the lift forces of individual cylinders, the summations of these forces and the turbulent components of the velocities. As an example of the results, Fig. 2 shows the time-frequency scalogram map (left subfigures) of the summation of the lift force coefficients C_L of the four cylinders and its time-averaged wavelet magnitude $\bar{S}(\tilde{n})$ (right subfigures) for at $\alpha = 0°, 22.5°,$ and $45°$. The wavelet analysis results show that the vortices are shed with a dominant frequency approximately half of that for an isolated square cylinder. This suggests that the whole cluster behaves as a single larger square cylinder with a width approximately $2D$. This remark is summarised in Fig. 3, in which Fig. 3a shows the dominant reduced frequencies for an isolated cylinder and for the considered cluster. Fig. 3 shows the ratio between the reduced frequency of isolated cylinder and that of the cluster. It can be seen that the ratio is varying around a value of 2.

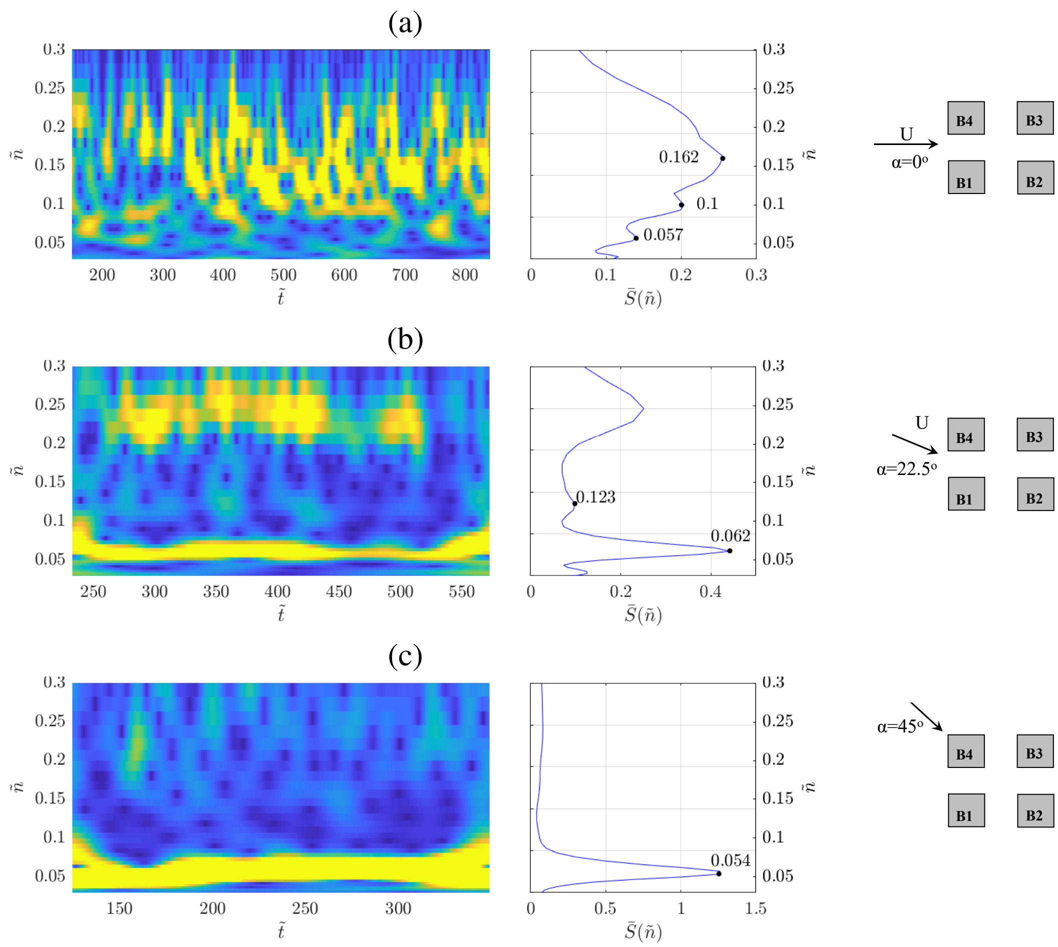

Figure 2. Time-frequency scalogram map (left) and the time-averaged wavelet magnitude (right) of the sum of lift force coefficients of the four cylinders for (a) $\alpha = 0°$; (b) $\alpha = 22.5°$; (c) $\alpha = 45°$

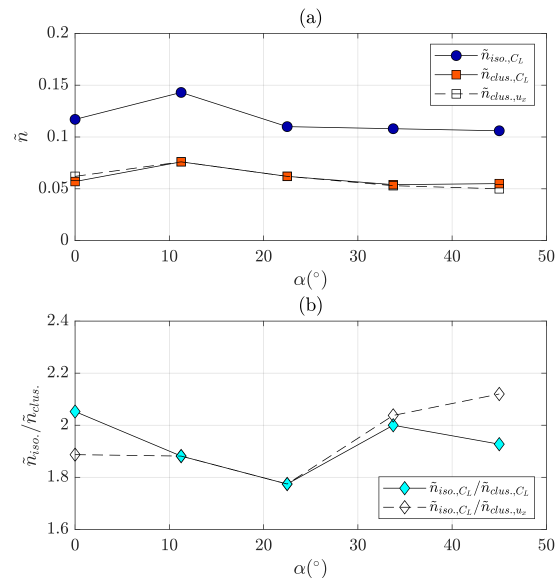

Figure 3. Dominant reduced frequencies of the cluster (a) and an isolated cylinder and the respective ratio (b). $\tilde{n}_{clus.,C_L}$ and $\tilde{n}_{clus.,u_x}$ are the dominant reduced frequencies of the cluster, calculated from C_L and u_x, respectively. $\tilde{n}_{sing.,C_L}$ is the dominant reduced frequency of an isolated cylinder at Re =46,000 (Mueller, 2012) calculated from C_L.

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