Cluster Effects of Tall Buildings

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1 INTRODUCTION

Many cities around the world are growing rapidly and tall buildings are being constructed to accommodate the increase in population and commercial activities. These high, slender structures can affect the urban fluid dynamics environment e.g., street-level winds, pollutants, heat, and temperature. When tall buildings are clustered together, a much more complex flow may be observed in the near and far field due to the shedding of asymmetric vortices coupled with the mutual interactions of the individual buildings' wakes. The wake from a cluster of tall buildings lasts for a much longer distance than low-rise buildings and a single tall building [1-2]. In order to understand the wake flow structure of from a cluster of tall buildings, it is crucial to setup a domain much greater than the neighbourhood scale, along with a Reynolds number (based on the building width) greater than a critical threshold, i.e. Re $\approx$ 2x10^4. Many wind tunnel facilities struggle to satisfy the requirement of a large domain due to the scale ratio constraint, suggesting that numerical simulations should play a crucial role for the studies of the cluster effect of tall buildings. These numerical simulations require high computational resources, and their accuracy is inevitably compromised depending on the size of urban area, number of tall buildings and spatial resolution.

The research reported in this paper is part of the project "Fluid Dynamics of Urban Tall building clUsters for Resilient built Environments (FUTURE)''. The present work expands the line of inquiry started in [2], which reported that the characteristic length scale for vortex shedding is close to cluster size of a 2x2 square cylinders in smooth inflow conditions. This phenomenon is known as the "cluster effect''. For instance, in a 45° wind, the dominant dimensionless vortex shedding frequency (i.e., the Strouhal number St) of a 2x2 cluster scaled by 2b is very close to that of a single square cylinder, where b is the cylinder width and the spacing is b. The study [2] raised 4 open questions, 1) whether this scaling could be applied to different numbers of cylinders with different spacings? 2) what is the role of the inflow turbulence? 3) whether this scaling could be applied to a group of finite-height square cylinders (idealised tall buildings)? 4) whether this scaling could be applied to real-life tall building cluster, e.g. the city of London. This paper aims to addressing the first two questions. A conclusive remark is drawn regarding the scaling of dominant vortex shedding frequency for different cluster sizes with various spacings. It also aims to shed light on the effect of free-stream turbulence (FST) as [3] commented that "There is not such an easy rule of thumb for the effects of the length scale". On-going studies [4] and [5] aim to address the third and fourth question above, respectively.

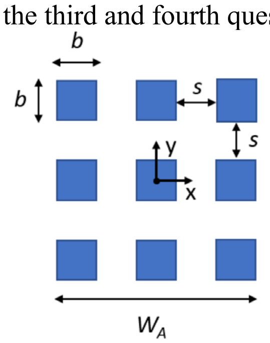

Figure 1 Plan view of the 3x3 cluster of square cylinders

2 COMPUTATIONAL SETUP

Several cases are considered, with 2×2, 3×3 and 4×4 clusters of square cylinders with dimensions of b×b×10b were simulated (Fig. 1), where the height of the cylinder is equal to domain height 10b. The Reynolds number is 6 × 10^6 based on the freestream velocity (U_∞ = 1m/s) and cylinder width (b=60m)

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for smooth and turbulent inflows. A flow incidence angle α =45° and four spacings 0.5b, b, 1.5b, 2b were simulated. The open source code PALM [6] along with the synthetic inflow generation method [7] was used, which is a parallelized LES model for the atmospheric boundary layer. The audience is referred to [6] for more details, e.g. the governing equations and standard parameters. A periodic boundary condition was applied at the two lateral (north and south) boundaries, while Neuman (free slip) boundary condition was used for the top boundary. No-slip wall boundary condition was used for the bottom boundary including buildings. The computational domain size was 72b×120b×10b. A structured mesh was used, where the total number of cells is 1.06 billion.

3 CLUSTERS OF SQUARE CYLINDERS IN SMOOTH INFLOW

Nguyen et al. (2023) [2] reported that for a 2×2 array of square cylinders with spacing *b* at various flow incidence angles in smooth inflow, the Strouhal number *St* of the vortex shedding process can be scaled by a characteristic cluster size approximately equal to 2*b*. In other words, the shedding frequency is governed by the size of the solid part with such a spacing *b*. The question arises herein whether the characteristic cluster size still holds for other clusters of square cylinders with different spacings and number of cylinders.

First of all, the cluster size W_A is expressed as $W_A = nb + mrb$, where m is the number of spacings across the frontal column of cylinders, n is the number of frontal column cylinders, and r is the ratio of the street width *s* to building width b (Fig. 1). The ratio *r* can be re-written in the following form

$$\epsilon = r - 1 \tag{1}$$

In Eq. (1), ϵ is a small non-dimensional factor, varying from -0.5 to 1 for the spacing *s* from 0.5 to 2. The ϵ can be viewed as a correction factor for considering the cluster porosity (e.g. the total spacing to the physical cluster size W_A), based on the fact that the Strouhal number *St* is governed by the size *2b* of the solid part for a 2×2 array with a spacing *b* resulting in $\epsilon = 0$. From the above equations, a non-dimensional vortex shedding frequency for the cluster St is written as follows,

$$St = \frac{fnb}{U_\infty}\left(1 + \epsilon\frac{m}{n+m}\right). \tag{2}$$

This affirms that the shedding frequency can be scaled by an effective cluster size $W_e = nb(1 + \frac{\epsilon m}{n+m})$, as the primary shedding frequency of an array of infinite-height cylinders normalised by the effective cluster size W_e and the freestream velocity U_∞, i.e., the Strouhal number St, is very close to that of an isolated single cylinder. Equation (2) suggests that the cluster Strouhal number is mostly dependent on the solid part of the cluster, with a small correction required for various spacings.

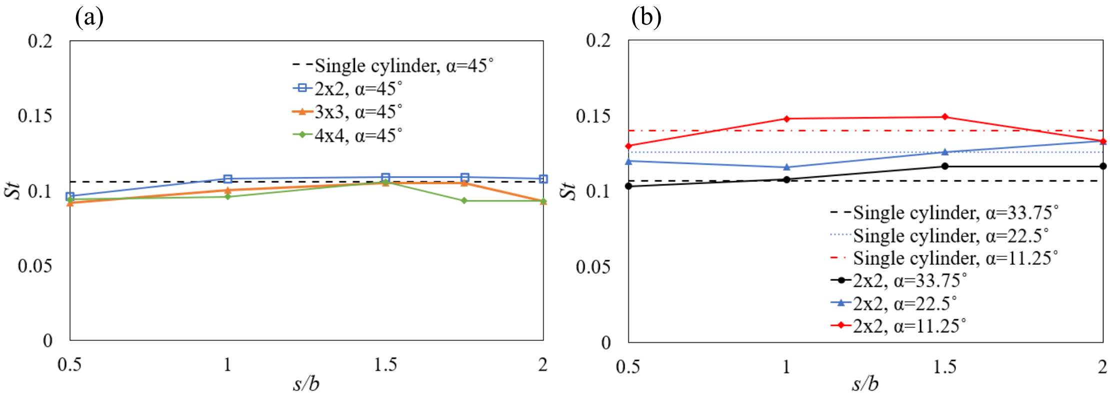

Figure 2. Strouhal numbers St for (a) the clusters of 2×2, 3x3 and 4x4 in smooth inflow flow for different spacings at $\alpha = 45^\circ$ and (b) the cluster of 2×2 cylinders at $\alpha = 33.75°, 22.5°$ and $11.25°$

Fig. 2a shows the cluster Strouhal numbers for a range of the spacings from 0.5 to 2, a range of

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cylinder numbers and in a wind direction $\alpha = 45°$, compared to the isolated cylinder. The Strouhal numbers for the single cylinder and the cluster are almost the same, respectively. This further confirms that the shedding frequency can be scaled by the effective cluster width W_e. Fig. 2b shows the Strouhal numbers of the cluster of 2×2 square cylinders with various spacings in $\alpha = 33.75°, 22.5°$ and $11.25°$ winds, compared with those for isolated square cylinders (Mueller, 2012). Again, the Strouhal numbers for the cluster are almost the same as those for the isolated square cylinder, respectively.

4 CLUSTERS OF SQUARE CYLINDERS IN TURBULENT INFLOW

Table 1 shows the simulated clusters of 2x2 square cylinders in isotropic freestream turbulence (FST) inflows. The turbulence intensity was fixed at 20%, while the integral length scales varied from 1b to 8b.

Table 1. List of simulated clusters of 2×2 cylinders in isotropic freestream turbulence (FST). Turbulence intensity of 20% was specified at the inlet. ILS is the integral length scale. See Eq. (1) for *r*

Case	Size	*s* (*b*)	W_A	*r*	*ILS/b*
N2-1-FST-L1	2x2	1	3	1	1
N2-1-FST-L2	2x2	1	3	1	2
N2-1-FST-L4	2x2	1	3	1	4
N2-1-FST-L8	2x2	1	3	1	8
N2-2-FST-L1	2x2	2	4	1	1
N2-2-FST-L2	2x2	2	4	1	2
N2-2-FST-L4	2x2	2	4	1	4

Figure 3 shows the Strouhal numbers for different cluster configurations and for isolated square cylinders in FST with different isotropic integral length scales in various wind directions. It is evident that St decreases by increasing the eddy size, i.e, the integral length scale of the inflow turbulence. However, the reduction in St, compared to the smooth inflow, is small for the integral length scale smaller than the cluster size i.e., $2b$. For instance, for the 2×2 cluster case N2-1-FST-1 ($s = b, ILS = b$), St reduces to 0.1, whereas for the case N2-1-FST-8 with large integral length scale ($s = b, ILS = 8b$), the reduction in Strouhal number is more pronounced ($St = 0.088$). The latter case suggests that when the FST integral length scale is approximately three times the cluster size W_A, the Strouhal number St is reduced by up to 18%. It is important to note that the St number for spacing $2b$ is not reduced to a similar extent as observed for spacing b. This is due to the reduced ratio of the freestream integral length scale to the cluster size.

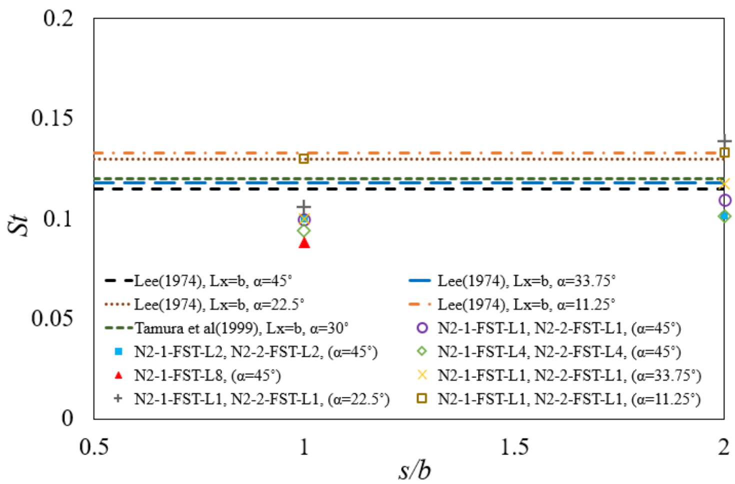

Figure 3. Strouhal number St for the clusters (dots) and for isolated cylinder (lines) for incoming FST for different flow angles and spacings

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5 CONCLUSIONS

This paper investigates the aerodynamical cluster effect of arrays of 2x2, 3x3 and 4x4 square cylinders in smooth and turbulent inflow. Different spacings, i.e., s=0.5b, b, 1.5b, 2b were considered. The primary vortex shedding frequency of infinite height square cylinders can be scaled by the effective cluster size $W_e = nb(1 + \varepsilon m/(n + m))$, where n and m are respectively the number of frontal column cylinders and the number of spacings across the frontal column of cylinders, and $\varepsilon = s/b - 1$ is the small difference between the spacing (s) to building width (b) ratio and unity. Firstly, the primary shedding frequency of an array of finite-height buildings normalized by the effective cluster size W_e and the freestream velocity U_i, i.e., the Strouhal number St, was very close to that of an isolated single building. The consistency of the data suggests that the aforementioned scaling law can be used for the vortex shedding frequency and for assessing the resulting wake flow behind an array of tall buildings. Second, for incoming free-stream turbulence with a large integral length scale (i.e., greater than the cluster size), the dominant Strouhal number of the arrays of infinite height square cylinders is reduced evidently compared to the smooth inflow.

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