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# The turbulent wake behind side-by-side plates

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**Abstract.** The wake behind two flat plates placed side by side normal to the inflow has been investigated by direct numerical simulation. The spacing between the two plates is one plate width  $d$  and the Reynolds number based on the plate width and inflow velocity is 1000. Flow pattern study indicates an anti-phase vortex shedding behind flat plates in the near wake which merges to one large wake downstream. Such a vortex structure has not been observed behind the flat plates for this gap ratio.

## 1. Introduction

Wake flow around bluff bodies such as circular cylinders has been the focus of attention for many researches. This is mostly due to the wide industrial applications, as well as the interesting flow physics of this problem. The wake behind a single flat plate normal to the inflow resembles in many ways the wake behind a circular cylinder although the separation points are fixed. The plate wake becomes turbulent at Reynolds numbers ( $Re$ ) based on the plate width  $d$  and the inflow velocity  $U_0$ , lower than the critical  $Re$  for cylinder wakes. At  $Re = 750$ , for instance, the wake was undoubtedly turbulent with a Strouhal number  $St = 0.168$ ; (Narasimhamurthy & Andersson, 2009).

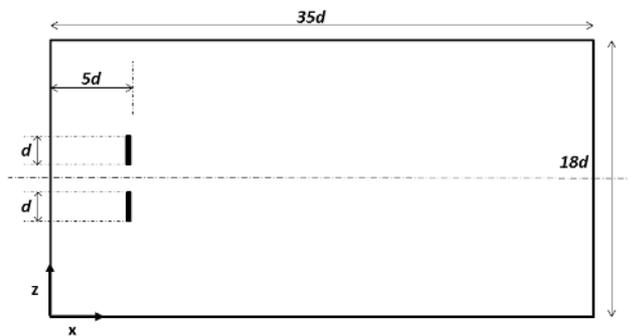
When we have two bluff bodies close to each other, the wake pattern becomes much more complicated. It is well known that the wake of a circular cylinder will interact with the wake of another cylinder if the distance,  $g$ , between the two bodies is relatively small. The interference between the two cylinder wakes was studied by Zdravkovich (1987), who identified three different flow regimes for side-by-side arrangements depending on the gap ratio  $g/d$ . Williamson (1985) investigated in-phase and anti-phase vortex shedding for different gap ratios for two side by side circular cylinders. The wake behind side by side flat plates has been investigated experimentally by Higuchi *et al.* (1994). In this paper results from a computational study of the wake behind two side-by-side flat plates normal to the inflow are presented.

## 2. Flow definition and numerical method

Direct numerical simulation (DNS) of the flow behind two side by side normal flat plates has been carried out by using the finite-volume code MGLET (Manhart, 2004). The three-dimensional Navier-Stokes equations are integrated in time for incompressible fluid. The code is based on

$2^{nd}$ -order central differencing scheme for spatial discretization and  $3^{rd}$ -order explicit Runge-Kutta scheme for marching in time with an iterative SIP (strongly implicit procedure) solver for Poisson equation on staggered Cartesian grid. A direct forcing immersed boundary method is employed to represent the solid-body inside the fluid-domain by means of internal boundary condition at the Cartesian grid points (Peller *et al.*, 2006). The two flat plates are normal to the inflow and the distance between them is chosen to be one plate width  $d$ . The thickness of the plates is  $0.02d$ . Reynolds number based on one plate width  $d$  and uniform inflow velocity  $U_0$  is set to 1000. All spatial dimensions and velocities are normalized by the plate width and inflow velocity. The size of the computational domain is  $L_x = 35d$ ,  $L_y = 6d$  and  $L_z = 18d$  (Figure 1) and the number of grid points is  $704 \times 120 \times 464$ .

Boundary conditions in this simulation include uniform inflow velocity without any free-stream perturbation at inlet, free slip boundary condition for the top and bottom walls, periodic boundary condition for the side walls and Neumann boundary condition at outlet. The time step is chosen to be  $\Delta t = 0.0005d/U_0$ .



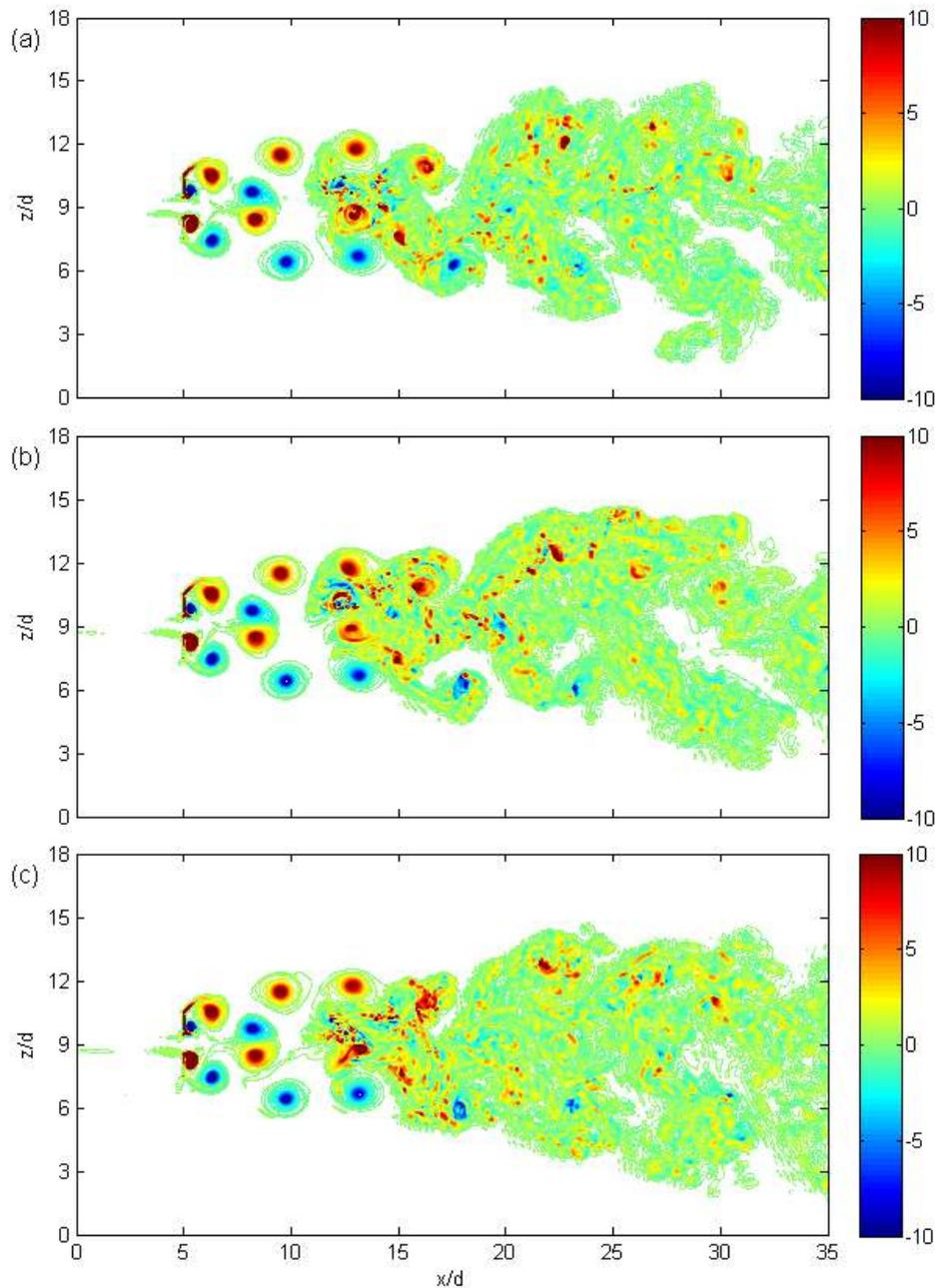
**Figure 1.** Computational domain, front view (not to scale).

### 3. Results and discussion

Figure 2 shows the instantaneous spanwise vorticity field at different spanwise planes. In these cross-sectional planes, from a large-scale point of view, the vorticity has almost the same feature. Figure 2 also indicates that both the near-wakes are equal in size, however, the two vortex streets are coupled and exhibits symmetry along the gap axis. Such an anti-phase vortex shedding was also observed behind two square cylinders with gap ratio  $g/d = 1.5$  and Reynolds number  $Re = 2262$  by Yen & Liu (2011) in their experimental work. In addition, Higuchi *et al.* (1994) have found a similar wake pattern behind two flat plates for  $g/d = 2$ . However, they reported asymmetric wake at gap ratio  $g/d = 1$ , which is in contrast to the present observation. This discrepancy can be due to the different Reynolds number and plate thickness used in both the studies. Reynolds number in their experiment was 1500 and the plate thickness was around 10 times larger than ours. Zdravkovich (1987) has reported such a coupled vortex street for  $g/d > 1.7$  for two circular cylinders, and it has not been observed behind the side-by-side plates for  $g/d = 1$ .

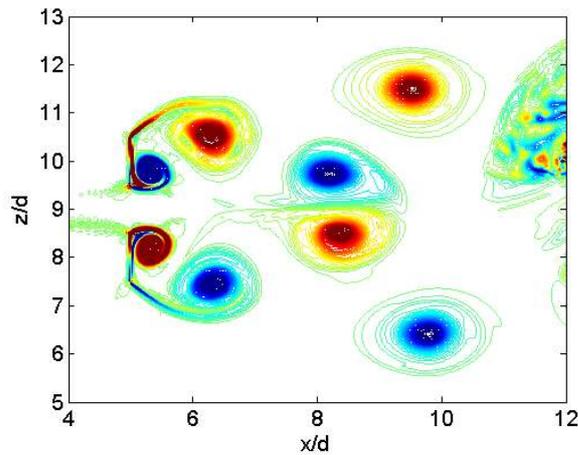
Figure 3 shows a close up of the near wake vortex structure. It is evident that the two shear layers separated from the inner gap edges, roll up differently from the shear layers separated from the outer free edges of the plates. The gap is not wide enough for the vortices to roll-up independently and structures in the inner wake are therefore slightly deformed.

The near-wake becomes distinctly destabilized  $5d - 8d$  downstream of the plates and it is noteworthy that the destabilization first occurs in the central part of the wake, i.e. downstream of the gap. The Karman vortices which emerged from the outer shear layers still remain almost regular. The distinct differences between the outer and inner shear layers are probably due to the



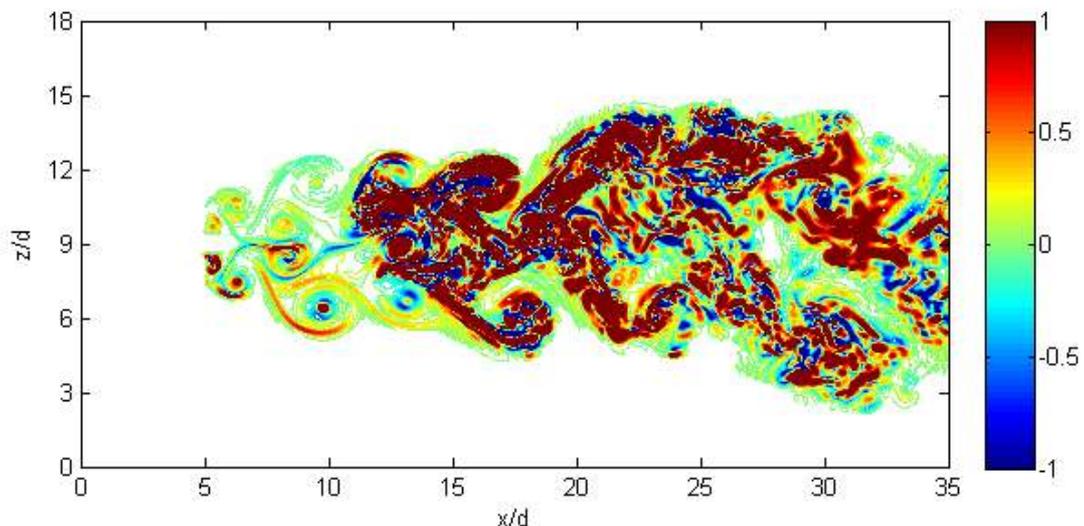
**Figure 2.** Instantaneous spanwise vorticity field at different cross section planes along the span: (a)  $y/d = 1.5$ ; (b)  $y/d = 3$ ; (c)  $y/d = 4.5$ . Plates are positioned at  $x/d = 5$ .

higher shear rates in the latter due to the substantial flow acceleration through the gap. About  $10d$  downstream of the plates (see Figure 2), the wake flow appears completely destabilized and fully turbulent. The symmetry about the geometrical center-plane does no longer exist and the flow appears as a single vortex street with alternating large-scale vortices. In contrast, at low Reynolds number (around 200) Williamson (1985) observed that anti-phase vortex streets keep their pattern and are stable. Nevertheless a combined wake structure, similar to what we have



**Figure 3.** Near wake pattern of instantaneous spanwise vorticity at spanwise cross section plane  $y/d = 3$ .

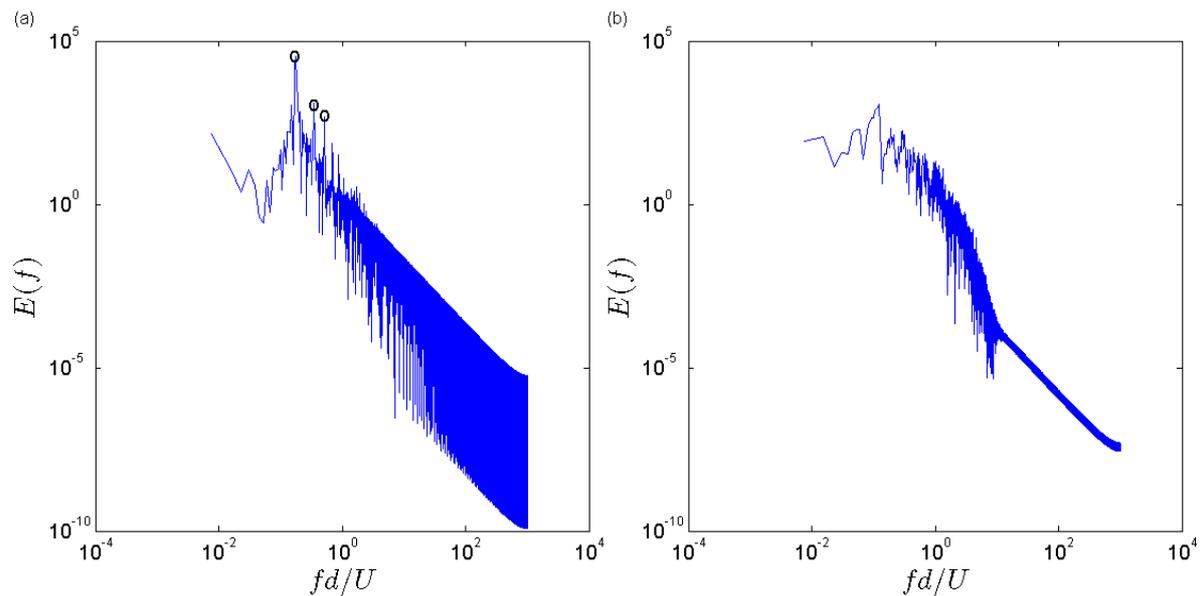
found here, was reported by Higuchi *et al.* (1994) at high Reynolds number ( $Re = 1500$ ). The instantaneous streamwise vorticity field in Figure 4 clearly demonstrates the anisotropic nature of the wake flow. Observe that there is an order of magnitude (10) difference when compared to the spanwise vorticity field in Figure 2(b).



**Figure 4.** Instantaneous streamwise vorticity field at spanwise cross section plane  $y/d = 3$  in Fig.2 (b).

In order to calculate shedding frequency, the time trace of cross-stream velocity  $w$  was sampled along lines parallel to the plates at  $2d$  and  $20d$  downstream of outer edge of both plates ( $z/d = 7.5$  &  $10.5$ ). The total sampling time was  $140d/U_0$  which is approximately equal to 28 shedding cycles. The power spectra of the velocity data using Fast Fourier Transform (FFT) is shown in Figure 5. In the near wake ( $2d$  downstream) we found that the shedding frequency is the same on both sides of wake. The velocity power spectrum shows the dominant frequency (Strouhal number  $St = fd/U_0$ ) is about 0.1755. We have observed two and three times of the dominant frequency in the wake, which is 0.3433 and 0.5188. These harmonic

frequencies may indicate that we have transitional wake flow in the near wake. Further study is needed to identify more details of the near wake structure.



**Figure 5.** Velocity power spectrum (a) at near wake ( $2d$  downstream);  $St = 0.1755, 0.3433$  &  $0.5188$  are marked by  $\circ$  and (b) at turbulent part ( $20d$  downstream)

In the turbulent part ( $20d$  downstream) the Strouhal number is different from the near wake. Although the symmetry has been broken by transition to turbulence, the shedding frequency is surprisingly the same on both sides of the wake. However, the Strouhal number based on  $d$  has been reduced to 0.12 in the turbulent part of the wake. If  $St$  is chosen to be based on the overall width of the configuration,  $3d$ , then it will be equal to 0.36 which seems abnormally high.

For more understanding, the mean drag coefficient is calculated. The obtained values are around 3.3 for one of the plates and 3.4 for the other, which are surprisingly high. This may be due to the short sampling time adopted for the averaging process. Further investigation will be carried out by the authors in order to clarify these matters.

#### 4. Conclusion

The wake behind two flat plates placed side by side and normal to the inflow has been investigated by DNS. Instantaneous vorticity structures are presented. Flow pattern study indicated an anti-phase vortex shedding behind flat plates for gap ratio  $g/d = 1$  in the near wake which merges to one large wake downstream. Such a coupled vortex street has not been observed behind the flat plates for this gap ratio. Shedding frequency in the form of Strouhal number and mean drag coefficient were calculated and reported. Mean drag coefficients were surprisingly high which can be the result of short time sampling. Further investigation is needed to clarify these matters.

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