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Turbulent wake behind two intersecting flat plates☆

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ABSTRACT

We have considered the three-dimensional wake behind a cross formed by two intersecting flat plates using direct numerical simulations. The Reynolds number based on the uniform inflow velocity U_0 and the plate width d was 1000. The vortex shedding in the wake was totally suppressed in a 4d wide intersection region and this gave rise to a massive zone of recirculating flow. Quasi two-dimensional vortex shedding with a primary frequency 0.165 U_0/d occurred behind the outer branches more than 7d from the intersection. The wake behind the outer branches of the crossing plates closely resembled the wake behind a single flat plate. However, the wake flow in an intermediate region (located between the intersection region and the outer branches) was affected by persistent secondary flows. Further, shear-layer (K-H) instabilities have been observed in this region. The mean wake structure revealed the formation of four symmetrically positioned pairs of swirling vortices close to the intersection corner next to the plate's edges.

1. Introduction

The intricate flow field around bluff bodies has captured the attention of numerous researchers due to the physical complexity of bluff-body wakes as well as the great variety of industrial applications. There also exists a considerable amount of literature investigating the interference of two bluff bodies, notably circular cylinders in close proximity as reviewed by Zdravkovich (1977). Another complex wake interaction takes place in the case of intersecting bluff bodies, where the wake flow characteristics are significantly altered. Interactions between wakes from the different branches of an intersecting structure may promote mixing, increase incoherent motions, and alter the formation length. The severe distortion introduced by the intersection, interrupts the vortex shedding process and may give rise to vortex dislocations in the wake or even initiate instabilities in the separated shear layers. Practical examples of such intersecting structures can be found in a wide range of engineering applications, such as supporting structures of offshore platforms, fish-net in the aquaculture industry (Lader et al., 2014) (in idealized situations where deformations of the net are negligible), fractal and non-fractal grids generating turbulence (Laizet and Vassilicos, 2011; Hurst and Vassilicos, 2007), heat exchangers (Segers et al., 2013), etc.

A typical geometry consists of two members, arranged perpendicular to each other in the shape of a cross. A cross made up of two intersecting cylinders can be considered as a prototype model of more general configurations. The turbulent wake behind two intersecting circular cylinders was studied by Osaka et al. (1983). They measured the mean and turbulent flow field of the far-wake of the intersecting cylinders in their wind tunnel. Osaka et al. (1983) confirmed the existence of the secondary flow - regarded as a secondary current of the second kind classified by Prandtl (1952) - which produced four pairs of vortices which are symmetric with respect to the geometrical symmetric planes. However they didn't investigate the origin of the vortices. Later on, Zdravkovich (1985) studied the structure of the three-dimensional near-wake behind two intersecting circular cylinders. He visualized the four symmetrically positioned pairs of streamwise vortices that originated from the surface of the cylinders. For two intersecting flat plates Donoso et al. (1983) studied the effect of intersection upon the vortex shedding from each member. However they did not investigate the development of the vortices in the wake of the intersecting plates although they mentioned their existence. Wind tunnel experimental results of two intersecting cylinders with circular and square sections were reported by Fox and Toy (1990). Other investigations have been concerned with the wake flow

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behind two overlaying or displaced perpendicular cylinders (Fox and Toy, 1988; Fox, 1992; Zdravkovich, 1983). More recently, Djenidi (2008) explored numerically the wake flow of a cross-bar with a bi-plane structure using the lattice Boltzmann method. In spite of the different experiments on intersecting structures, only a few numerical investigations have explored the complex three-dimensional wake structure of intersecting cylinders. In the present study, the wake structure behind a structure consisting of two flat plates forming a cross is studied numerically by Direct Numerical Simulation (DNS) at Reynolds number 1000. Among different computational approaches, solutions of the full Navier–Stokes equations (by DNS) is the only tool which can help us to faithfully explore the complex wake structure in detail. Some fundamental studies of the wake structure behind a single normal flat plate have been carried out using this method; e. g. the vortex formation behind a uniform, i.e. 2D, flat plate studied by Najjar and Balachandar (1998), Saha (2007) and Narasimhamurthy and Andersson (2009), among others. Due to the enormous range of time and length scales which need to be resolved in DNS, this method is very expensive. DNS can only be applied to fairly simple geometrical configurations and at relatively low Reynolds numbers due to still limited computational resources. Among all studies regarding the evaluation of the quality of DNS, we can refer to the work by Laizet et al. (2015) on the influence of the spatial resolution in DNS of a single square grid.

The present study aims to gain more insight regarding the complex three dimensional wake structures. The similarities and differences between the flow behind the intersecting plates and circular cylinders are presented and the influence of the severe distortion caused by the intersecting plates on the near-wake characteristics as well as the separated shear layers is discussed. The wake flow is characterized by three qualitatively different flow regimes: regime A) the intersection region ($|y/d| \lesssim 2$) with massive separated flow where vortex shedding is suppressed; regime C) behind the outer branches ($|y/d| \gtrsim 7$) with quasi two-dimensional vortex shedding; and the intermediate regime B) in between ($2 \lesssim |y/d| \lesssim 7$) where the flow gradually changes from fully three-dimensional to quasi two-dimensional flow. The intersecting flat plates were chosen due to their fixed separation points at the plate edges rather than *a priori* unknown ones at the curved surface of a circular cylinder. In this paper, we first present the flow configuration and the numerical method in Section 2. Then in Section 3, the wake dynamics are studied by means of vortical structures accompanied by a discussion on the shear-layer instability and the corresponding frequencies. Then, we proceed to investigate the topology of the mean wake structure. First- and second-order statistics are presented next and the results for the outer part of the branches will be evaluated and compared with previous findings for flow behind a single flat plate. Higher-order statistics are also examined in order to see if the velocity fluctuations in the wake depart from a Gaussian behavior. Finally, the paper is concluded in Section 4 where the main findings are emphasized.

2. Flow configuration and numerical method

The current bluff-body geometry consists of two intersecting flat plates placed normal to the inflow. The whole geometry is positioned in a single plane, where each of the two plates has an aspect ratio ($AR = l/d$; with l and d the total length and width of one plate) of 31. In order to mimic infinitely thin plates, the thickness of the intersecting plates is very small and equal to 0.02d The Reynolds number *Re* based on the inflow velocity U_0 and d, is 1000. The three-dimensional Navier–Stokes equations solved in time with an incompressible formulation are given in Eqs. (1) and (2):

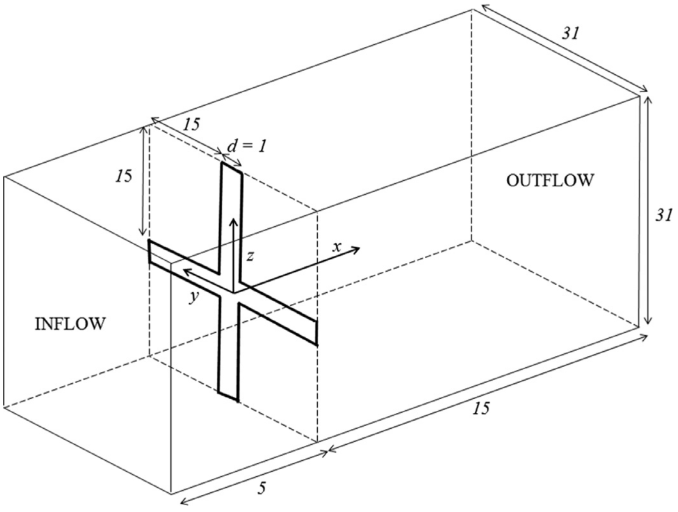

Fig. 1. Computational domain (not to scale). Note that the three different regions of interest in this study are: the intersection region $|y/d| \lesssim 2$ and $|z/d| \lesssim 2$ (flow regime A), and the (four) outer branches $|y/d| \gtrsim 7$ and $|z/d| \gtrsim 7$ (flow regime C) and the intermediate region in between $2 \lesssim |y/d| \lesssim 7$ and $2 \lesssim |z/d| \lesssim 7$ (flow regime B).

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial {x_j}^2}. \tag{2}$$

Direct Numerical Simulation of the flow past the configuration has been carried out by using the finite-volume code MGLET (Manhart, 2004). The code has a second-order central-differencing scheme for spatial discretization and a third-order explicit Runge–Kutta scheme for marching in time. The Poisson equation is solved by an iterative strongly implicit procedure (SIP). The code uses staggered Cartesian grid and the body surface is implemented in the grid by means of a direct forcing Immersed Boundary Method (Peller et al., 2006). All the spatial dimensions are normalized by the plate width d, and all velocities are scaled by inflow velocity U_0. The computational domain, as shown in Fig. 1, has a length 20d in streamwise and 31d in both spanwise and cross-stream directions. A preliminary simulation with a smaller domain size 20d × 21d × 21d was performed by the present authors (Dadmarzi et al., 2012).

The boundary conditions include the uniform inflow velocity without any free-stream perturbation at the inlet $x/d = -5$, and free-slip condition at the two vertical sides of the computational domain as well as along the top and the bottom planes. A Neumann boundary condition is used at the outlet. The time step is chosen to be $\Delta t = 0.001d/U_0$. The size of our computational domain in spanwise (y) and cross-stream (z) directions are comparable to previous experimental setups (Zdravkovich, 1985; Donoso et al., 1983; Fox and Toy, 1990) but due to computational limitations, our domain is not long enough in x-direction to investigate the behavior of the far wake. Since the outer branches intersect the two vertical planes of the computational domain ((x,z)-planes) as well as the top and bottom planes ((x,y)-planes), the free-slip boundary condition has an impact on the vortex dynamics close to the boundaries. The effect of the chosen boundary condition appears in a form of a tiny recirculation bubble just next to the surrounding computational planes. In this simulation our goal was to use a wide enough computational domain with high aspect ratio of the plates (compare to our preliminary simulation) in order to

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