Ocean Engineering 92 (2014) 212–233

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical study of aperiodic phenomena past two staggered rows of cylinders in cross-flow

P. Anagnostopoulos *, S.A. Seitanis

Aristotle University of Thessaloniki, Department of Civil Engineering, Thessaloniki 54124, Greece

ARTICLE INFO

Article history:
Received 14 October 2013
Accepted 24 September 2014

Keywords:
Cylinder row
Navier–Stokes equations
Flow visualization
Drag force
Lift force
Shedding frequency

ABSTRACT

The results of a numerical study of cross-flow past two staggered rows of cylinders are presented, at a fixed Reynolds number equal to 200. The upstream row comprised three and the downstream row four cylinders, for centre-to-centre pitch ratios in the streamwise direction, S/D, varying between 0 and 1. The distance between the centres of adjacent cylinders on the same row was equal to 3 cylinder diameters. The finite element method was employed for the solution. Significant fluctuations of the hydrodynamic forces, especially in the streamwise direction, were observed for all cylinders. Although for each longitudinal pitch ratio the variation of flow pattern with time appears almost chaotic, systematic attempt was made for the classification of the various flow regimes. A common characteristic of all longitudinal pitch ratios is the switch of wake width behind the cylinders of the downstream row. For $S/D \leq 0.5$ the formation of a large and symmetrical wake occurred intermittently past the downstream cylinders, with drastic impact on the entire flow domain. High shedding frequencies past the cylinders of the upstream row were detected for $S/D \leq 0.5$, which could reach two or even three times the shedding frequency past the cylinders of the downstream row.

1. Introduction

The investigation of flow through bundles of cylinders is a problem of great engineering interest, since it is related to various engineering applications. Although the initial field of application was heat exchangers, boilers and nuclear reactors, the phenomena are of increasing interest in Ocean Engineering, since there are various forms of offshore structures (pipelines, risers, spar platforms etc.) required mainly for the exploitation of hydrocarbon deposits, where there is cross-current on cylinders. Apart from the extensive experimental effort devoted to the problem, numerical investigations of flow through arrays of cylinders have been undertaken during the last decades, using various computational techniques. Sangani and Acrivos (1982) presented an analytical solution for the slow flow past periodic arrays of cylinders with application to heat transfer. Dhaubhadel et al. (1986, 1987) investigated the flow and heat transfer through bundles of cylinders of various arrangements, using a penalty finite element scheme. Ganoulis et al. (1989) used Laser-Doppler anemometry for the measurement of flow velocity through a periodic array of cylinders and compared the experimental measurements with results obtained numerically at similar conditions. Tezduyar and Liou (1990) used the stream function and vorticity formulation for the finite element solution of flow through arrays of cylinders. Rasoul et al. (1994) used the finite difference technique for the solution of laminar flow through an infinite depth staggered bundle of cylinders. They considered a unit cell in the streamwise direction and obtained by an iterative procedure the flow conditions when constant flow had been established after many wavelengths in the flow direction. Rorris et al. (1994, 1995) extended the solution to the full configuration of five staggered cylinder rows, at different pitch ratios. Their results revealed the effect of the cylinder array geometry on the flow pattern, and the development of flow behind consecutive cylinder rows. Braun and Kudriavtsev (1995) investigated numerically the flow structure in staggered banks of cylinders located in a channel, at Reynolds numbers ranging between 86 and 869. They also studied the flow past a single row of cylinders in the same range of Reynolds numbers. Sweeney and Meskell (2003) used a discrete vortex method to simulate vortex-shedding in tube arrays for Re = 2200, whereas Huang et al. (2006) used a commercial solver (FLUENT) for the numerical simulation of flow around rows of cylinders for Re ≤ 100. Lam et al. (2006) conducted a numerical simulation of cross-flow past a row of rigid and flexible cylinders at $Re = 2.67 \times 10^4$. Liang and Papadakis (2007) presented a large eddy simulation of cross-flow through a staggered tube bundle at

* Corresponding author. Tel.: +30 2310 995675; fax: +30 2310 995680.
E-mail address: anagnost@civil.auth.gr (P. Anagnostopoulos).

http://dx.doi.org/10.1016/j.oceaneng.2014.09.049
0029-8018/

Re=8600, and Paul et al. (2008) employed a commercial code (ANSYS CFX) for the investigation of cross-flow in a staggered tube bundle at Re=9300. More recently, Teyssedou et al. (2014) conducted simulations of cross-flow around in-line and staggered tube bundles, using the FLUENT software with several turbulence models.

Although early numerical solutions confined the solution domain in "unit cells", the phenomenon is more complex than the assumption of flow through unit cells or rows of half-cylinders. In addition, although the literature through deep rows of cylinder is extensive, cross-flow past one or two rows of cylinders has received less attention. A significant contribution is that of Roberts (1966), who conducted an experimental study in order to investigate the vibratory motion of a cascade of closely spaced circular cylinders. Based on the assumption that the flow field is periodic in the direction across the cascade, he measured the drag coefficients on two half cylinders and found that the cylinder with the narrow wake (upstream cylinder) experiences a greater drag than the cylinder with the wide wake (downstream cylinder). Zdravkovich (1987) reports that for the simpler case of flow past two cylinders in a side-by-side arrangement, narrow and wide wakes are formed behind the cylinders when the centre-to-centre transverse pitch ratio, T/D, lies between 1.2 and 2.2, and the gap flow forms a jet biased towards the narrow wake. The biased jet can switch to the opposite side at irregular time intervals, and the narrow and wide wakes behind the tubes interchange (bistable flow). Zdravkovich and Stonebanks (1990) examined the flow past a single row and two staggered rows of tubes. They found that the biased gap flows could intermittently switch direction (metastable flows). However, they concluded that the nonuniformity of gap flows was significant in the range $1.1 < T/D \leq 1.75$ and disappeared beyond $T/D=2.1$. They also noticed that the drag forces on the cylinders of the upstream row were higher than those of the downstream row, in agreement with the measurement conducted by Roberts. Le Gal et al. (1996) examined experimentally the cross-flow past a single row of cylinders, whereas Sumner et al. (1999) conducted experiments on cross-flow past two and three cylinders arranged side-by-side. Seitanis et al. (2005) examined experimentally the vibratory motion of a flexible row of three circular cylinders in the streamwise direction, placed alternately between four cylinders of a fixed row. The flexible row was oscillating upstream of the fixed row and the oscillation amplitude was not constant at different cycles for the same reduced velocity. Olinto et al. (2006) investigated experimentally the bistable flow past both a pair of cylinders and a parallel tube array of deep rows. More recently, de Paula and Möller (2012) conducted and experimental study of flow past two staggered rows of cylinders, and de Paula et al. (2013) investigated the bistability of wake behind three cylinders in triangular arrangement.

The objective of this study is the numerical solution of cross-flow past two staggered rows of cylinders in tandem, for longitudinal pitch ratios varying between 0 and 1, at a fixed Reynolds number equal to 200. The upstream row comprised three and the downstream row four cylinders, while the distance between the centres of adjacent cylinders on the same row was kept constant, equal to 3 cylinder diameters. For this spacing, the centre-to-centre distance between two adjacent cylinders of the whole arrangement is 1.5 cylinder diameters. This value lies between 1.1 and 1.75, which is the interval in which significant nonuniformity of gap flows was observed (Zdravkovich and Stonebanks, 1990).

The finite element technique was employed for the solution of the Navier-Stokes equations, in the formulation where the stream function, Ψ, and the vorticity, ζ, are the field variables. The vorticity contours were employed for the numerical flow visualization, whereas the time history of the drag and lift forces exerted on the three central cylinders are presented. The solution revealed the effect of the streamwise displacement between the two rows on the flow pattern and on the hydrodynamic forces exerted on the cylinders.

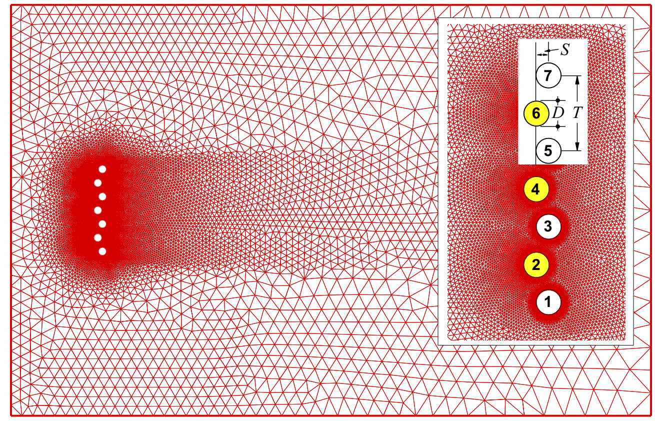

Fig. 1. The finite element mesh for $S/D=-0.5$. The magnified view near the cylinders inset contains the numbering convention of cylinders.

2. The computational technique

The mathematical model of the problem is composed by the Navier-Stokes equations, in the formulation where the stream function, Ψ, and the vorticity, ζ, are the field variables. In the Ψ-ζ formulation the governing equations become

$$\nabla^2 \Psi = -\zeta \tag{1}$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial \Psi}{\partial y}\frac{\partial \zeta}{\partial x}-\frac{\partial \Psi}{\partial x}\frac{\partial \zeta}{\partial y}=\nu\,\nabla^2\zeta \tag{2}$$

Eq. (1) is of Poisson's type, whereas Eq. (2) is the well-known diffusion-advection equation, appearing frequently in engineering practice. Application of the "characteristic-Galerkin" technique (Zienkiewicz and Taylor, 1991) for the time-discretization of Eq. (2) yields

$$\frac{\Delta \zeta}{\Delta t}+\frac{\partial \Psi}{\partial y}\frac{\partial \zeta}{\partial x}-\frac{\partial \Psi}{\partial x}\frac{\partial \zeta}{\partial y}=\nu\,\nabla^2\zeta+\frac{\partial}{\partial x}\left(\frac{u^2\Delta t}{2}\frac{\partial \zeta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{v^2\Delta t}{2}\frac{\partial \zeta}{\partial y}\right)+u\,v\,\Delta t\frac{\partial^2\zeta}{\partial x\partial y} \tag{3}$$

$\Delta\zeta$ represents the increment of nodal vorticity, $\zeta_{n+1}-\zeta_n$, between two successive time levels, n and $n+1$, separated by the time interval Δt. u and v are the two components of the fluid velocity, defined in terms of Ψ as: $u=\partial\Psi/\partial y$ and $v=-\partial\Psi/\partial x$.

Applying the Galerkin technique for each element to all terms of Eqs. (1) and (3) and assembling for the whole domain, the two following matrix relationships are obtained:

$$[K_1]\ \{\Psi\}_n=[K_2]\ \{\zeta\}_n+\{R_1\} \tag{4}$$

$$[K_3]\ \{\zeta\}_{n+1}+[K_4]\ \left\{\frac{\Delta\zeta}{\Delta t}\right\}+\{R_2\}+\{R_3\}=\{R_4\} \tag{5}$$

The coefficient matrices $[K_1]$, $[K_2]$, $[K_3]$ and $[K_4]$ are of square form, whereas $\{R_1\}$, $\{R_2\}$, $\{R_3\}$ and $\{R_4\}$ are column matrices (vectors). The vectors $\{R_1\}$ and $\{R_4\}$ contain the derivatives of Ψ and ζ with respect to the direction normal to the boundary, when the corresponding element lies on a boundary and a natural boundary condition for Ψ or ζ is specified. In the present case $\{R_1\}$ and $\{R_4\}$ are equal to zero. The matrix $\{R_3\}$ contains the contribution of the last three terms of Eq. (3), introduced from the application of the characteristic-Galerkin technique. The