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Int. J. Nav. Archit. Ocean Eng. (2015) 7:906~919
http://dx.doi.org/10.1515/ijnaoe-2015-0063
pISSN: 2092-6782, eISSN: 2092-6790

Experimental investigation of flow characteristics around four square-cylinder arrays at subcritical Reynolds numbers

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Received 22 April 2015; Revised 23 June 2015; Accepted 5 July 2015

ABSTRACT: *The Deep Draft Semi-Submersible (DDS) concepts are known for their favourable vertical motion performance. However, the DDS may experience critical Vortex-Induced Motion (VIM) stemming from the fluctuating forces on the columns. In order to investigate the current-induced excitation forces of VIM, an experimental study of flow characteristics around four square-section cylinders in a square configuration is presented. A number of column spacing ratios and array attack angles were considered to investigate the parametric influences. The results comprise flow patterns, drag and lift forces, as well as Strouhal numbers. It is shown that both the drag and lift forces acting on the cylinders are slightly different between the various L/D values, and the fluctuating forces peak at L/D = 4.14. The lift force of downstream cylinders reaches its maximum at around α = 15°. Furthermore, the flow around circular-section-cylinder arrays is also discussed in comparison with that of square cylinders.*

KEY WORDS: Deep draft semi-submersible (DDS); Experimental study; Four square-section cylinders; Spacing ratio; Array attack angle.

NOMENCLATURE

A_p	Projected area normal to the flow direction	H	height of square cylinder
C_D	drag coefficient ($=F_x/(0.5\times\rho U_\infty{}^2 A_p)$)	H/D	aspect ratio
$\bar{C}_D$	average drag coefficient for each cylinder	L	centre-to-centre cylinder spacing
C_L	lift coefficient ($=F_y/(0.5\times\rho U_\infty{}^2 A_p)$)	L/D	spacing ratio
$\bar{C}_L$	average lift coefficient for each cylinder	Re	Reynolds number ($=U_\infty D/\nu$)
C_{Lrms}	root-mean-square value of lift coefficient for each cylinder	St	Strouhal number ($=f_v D/U_\infty$)
		U_∞	free-stream velocity
D	width of square cylinder	α	attack angle
f_v	vortex-shedding frequency (Hz)	F_x	streamwise force component
F_y	cross-stream force component	ρ	air density
ν	kinetic viscosity of air		

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INTRODUCTION

Recently the effect of the sea current environment on the dynamic behaviour of floating offshore structures has become an important design issue. Because of potentially resulting in significant fatigue damage of moorings and risers, more recent work has indicated Vortex-Induced Motion (VIM) in addition to semi-submersible platforms, particularly with the development of Deep Draft Semi-submersible (DDS) concepts. Waals et al. (2007) carried out model tests to discuss the dynamic behaviour and the associated complex flow patterns of DDS and Tension Leg Platforms (TLP) in current. Goncalves et al. (2012; 2013) performed a series of tests to check the effects of different factors on the VIM of a semi-submersible platform with four square columns, considering such as current incidence angles, hull appendages, surface waves, the external damping level and draft conditions.

As a multi-column floater, the deep draft semi-submersible experiences the VIM similarly to that of a group of bluff bodies exposed to a cross flow. Therefore, aiming to understand the hydrodynamic excitation forces and the fluid mechanism of the VIM behaviour, it is essential to study vortex shedding characteristics and the resulting induced forces from the cross flow around the column arrays. Liu and Chen (2002) reported an experimental study on the flow around two square cylinders in a tandem arrangement with the spacing between the centres of the cylinders varying from 1.5 to 9 times the width of the cylinder at the Reynolds number ranging from 2.0×10^3 to 1.6×10^4. The experimental investigation stated that the flow characteristics around two cylinders in tandem depended strongly not only on the spacing ratio, but also on the arrangement form. Hasebe et al. (2009) conducted an experimental study on two square cylinders in tandem arrangement, and pay more attention to the flow field between two cylinders. The surface pressure distributions and the velocity between two cylinders were measured. Agrawal et al. (2006) examined the low-Reynolds number flow around two square cylinders placed side-by-side using the lattice Boltzmann method. They demonstrated the existence of both synchronized and flip-flop eddy shedding regimes with square cylinders, in agreement with the well known results for circular cylinders. Kumar et al. (2008) presented a simulation of flow around a row of nine square cylinders placed normal to the oncoming flow with spacing to diameter ratios of 0.3 to 12 and undertaken by the lattice Boltzmann method. No significant interaction between the individual wakes was observed with a spacing greater than six times the diameter.

Studies of the more complex wake flow around four-square-cylinder arrangements are still rather scarce and have not been well documented in the literature. Some investigations of the flow patterns for four circular section cylinders have been carried out using both experimental and numerical techniques over the past few years. Lam and Lo (1992) and Lam et al. (2003a) conducted flow visualization studies in order to understand the effects of the spacing ratio on both the flow patterns and vortex shedding frequencies. Moreover, Lam and Fang (1995) and Lam et al. (2003b) measured the drag and lift coefficients and the pressure distributions on four cylinders in a square configuration with various spacing ratios and array attack angles. However, investigations of the spacing ratio and the array attack angle effects on the flow characteristics for four cylinders in an in-line rectangular configuration are far from completed, especially at high Reynolds numbers for turbulent flow conditions. The present work aims to experimentally study the flow dynamics around four cylinders (of both circular and square section) grouped in a square configuration at subcritical Reynolds numbers. Three spacing ratios and four angles of incidence were investigated. In this study, particular attention is paid to the flow field around square cylinders as they are being increasingly considered by designers.

EXPERIMENTAL SETUP

Test conditions

The experiments were carried out in a closed circuit low-speed wind tunnel with a test section ($0.6\ m \times 0.8\ m \times 2.1\ m$, respectively, width $\times$ depth $\times$ length). The uniform flow into the test section had the maximum turbulence intensity 0.7% for the velocity ranged in the experiments. The four cylinder models, of $29\ mm \times 29\ mm$ square cross-section and with a 20.5 aspect ratio, were always positioned vertically oriented on the longitudinal centre line of the working section. All models were constructed from stainless steel, and had machined sharp edges. Each cylinder was essentially a rigid inflexible element. The blockage ratio (per cylinder) in the test section was 4.8% for the present experiments. For the single cylinder tests, this blockage falls within the single cylinder blockage reported in West and Apelt (1982) and in Schewe (1983). According to Ota et al. (1994), the blockage correction applied to the drag coefficients was $\approx$ 10.5%, which was estimated using the method based on