Applied Ocean Research 49 (2015) 20–26

Contents lists available at ScienceDirect

Applied Ocean Research

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

Force and flow characteristics of a circular cylinder with uniform surface roughness at subcritical Reynolds numbers

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ARTICLE INFO

Article history:
Received 26 April 2013
Received in revised form 9 June 2014
Accepted 10 June 2014

Keywords:
Drag coefficient
Drag reduction
Surface roughness
Rough cylinder
Dimple cylinder

ABSTRACT

The main purpose of this study is to establish a better understanding of the relationship between drag reduction and surface roughness. Experiments were conducted to measure the force and flow characteristics of a circular cylinder with different types of artificial surface roughness over the range $6 \times 10^3 < Re < 8 \times 10^4$ (Re is based on the cylinder diameter D). The roughness cylinder was formed by covering the exterior surface of the cylinder with uniformly distributed (1) sandpaper, (2) netting, and (3) dimples. The roughness coefficient ranged from $k/D = 0.0028$ to 0.025 (k is the roughness height). A detailed quantitative measurement of the flow field around the cylinder using Particle Imaging Velocimetry (PIV) was carried out. The hydrodynamic force coefficients (drag and lift) of the rough cylinders are compared against those of a smooth cylinder measured under the same flow conditions. It is found that certain configuration of surface roughness significantly reduces the mean drag coefficient of the cylinder, particularly at large Reynolds numbers. In addition, the root-mean-square (r.m.s.) lift coefficient of the rough cylinders is considerably lower than that of a smooth cylinder.

1. Introduction

Cylindrical structures are widely used in offshore and marine engineering, such as platform pillars, pipelines and risers. Many researchers have explored the concept of controlling the flow over circular cylinders in order to reduce the drag force and vortex-induced vibration of the structure, by using some form of add-on devices, including splitter plates [3,7] and helical strakes [11,16]. These studies showed that such devices could suppress the interactions between the two shear layers separated from either side of the cylinder, and hence lead to partial or complete elimination of vortex shedding in the wake. However, splitter plates are useful for certain current direction only, and helical strakes would increase the drag force compared to that of a smooth cylinder of the same diameter.

The concept of controlling the hydrodynamic forces on circular cylinders by introducing artificial roughness on the exterior surface is not new. A large number of studies have been reported to assess the effectiveness of different roughness patterns, see for example Achenbach [2] on sand roughness ($4 \times 10^4 \leq Re \leq 3 \times 10^6$); Nakamura and Tomonari [12] on roughness strips ($4 \times 10^4 \leq Re \leq 1.7 \times 10^6$); Bearman and Harvey [4] on dimpled surface ($2 \times 10^4 \leq Re \leq 3 \times 10^5$); Kimura and Tsutahara [9] and Huang et al. [8] on grooves of various shapes ($2 \times 10^4 \leq Re \leq 4 \times 10^5$). These studies bring to light the fact that hydrodynamic forces on a cylinder could be modified through the introduction of pertinent roughness patterns. For example, Huang et al. [8] compared the results of the smooth and grooved cylinders and showed that helical grooves reduced the drag loading by between 18 and 25%.

It appears that a roughness coefficient k/D (k is the roughness height, such as the groove depth or dimple depth; D is the cylinder diameter) of around 0.01 is the most effective. The previous studies [2,5,10,13] indicated that the surface roughness does not only reduce the mean drag on the cylinder, but also leads to lower critical Reynolds numbers.

Despite these efforts, it appears that a rigorous understanding of the fundamental mechanism of different types of roughness is still missing. Most of the existing studies focused on force measurements of the cylinders primarily in air over a limited roughness range. However, quantitative measurements of the flow field around rough cylinders are relatively scarce, so the flow behaviours (such as mean/r.m.s. lift and drag coefficients, vortex shedding frequency) could not be generalized.

The purpose of this study is to complement the previous studies by providing Particle Imaging Velocimetry (PIV) measurements of the flow around the cylinder in conjunction with concurrent measurement of the dynamic forces (lift/drag) on the cylinder. PIV is an optical method of flow visualization, which is able to obtain the whole-field, instantaneous velocity distributions and has been widely used in the literature for quantitative measurement of flow structure.

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0141-1187/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2014.06.002

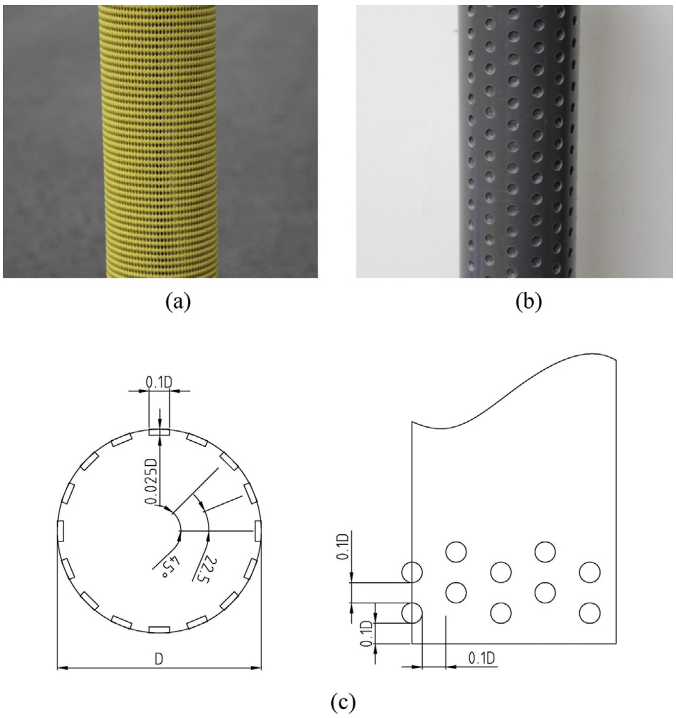

Fig. 1. The rough cylinders with (a) netting and (b) dimples. (c) Sketch showing details of the dimples.

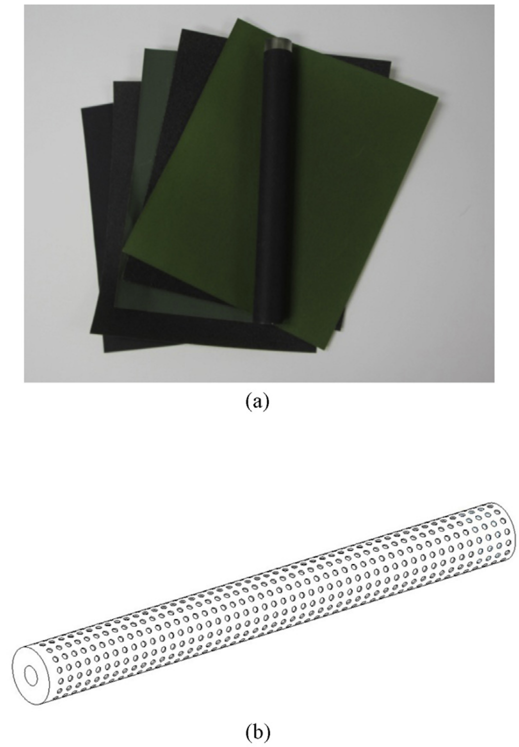

Fig. 3. The test cylinders in the open channel: (a) rough cylinder; and (b) dimple cylinder.

2. Methodology

Two series of model tests were carried out on two different sizes of cylinder at D= (a) 100 mm in a towing tank, and (b) 29 mm in a re-circulating water channel. Test (a) has the advantage of larger model and Reynolds number, whereas Test (b) in a small channel could be conducted to study the detailed flow patterns using Particle Imaging Velocimetry (PIV).

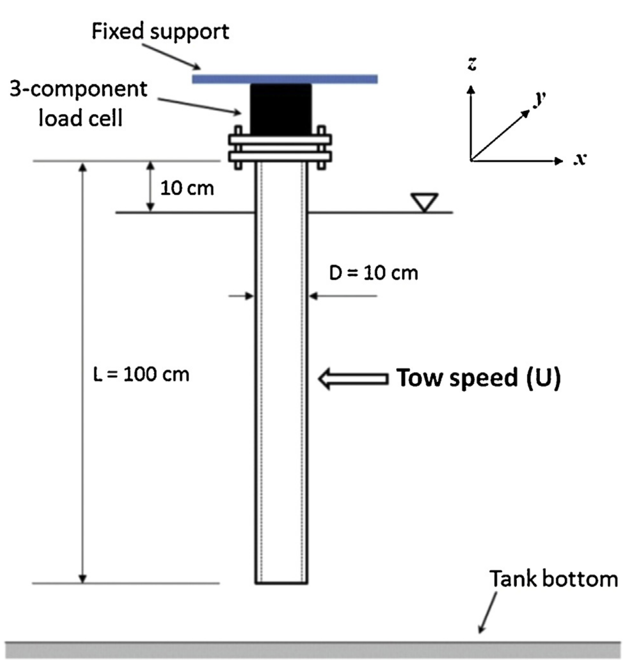

Fig. 2. Schematic of the force measurements.

2.1. Model test in a towing tank

The tests were performed in a towing tank located at the Hydraulics Laboratory, School of Civil and Environmental Engineering, Nanyang Technological University (NTU). The rectangular test section is 4000 mm × 1500 mm (width × depth). A motorized carriage was used to tow the cylinder model at any desired speed up to 1.0 m/s.

The smooth cylinder was made of stainless steel tube with length, L = 1000 mm and diameter, D = 100 mm. The exterior surfaces of the tube were polished. The rough cylinder was made by uniformly wrapping a layer of netting around the smooth cylinder (see Fig. 1(a)). The thickness of the netting was 2 mm, and hence the roughness coefficient is $k/D = 0.02$. The dimple cylinder was made of PVC pipe of the same diameter and indented to produce an array of shallow dimples (16 equally spaced dimples along a circumference) on its surface (see Fig. 1(b) and (c)). The radius (r) and depth (k) of dimples are 0.05D and 0.025D ($k/D = 0.025$), respectively. The dimple design in the present study followed that of Bearman and Harvey [4] which had 12 equally spaced dimples along the circumference with the dimple radius 0.05D and the dimple depth 0.009D, respectively. The towing speed was set at 0.2, 0.4, 0.6 and 0.8 m/s, yielding the Reynolds number range $20{,}000 \leq Re \leq 80{,}000$.

A 3-component piezoelectric load cell was mounted on the top of the model cylinder and connected to the carriage platform rigidly (see Fig. 2). In this way, the dynamic drag (F_D) and lift (F_L) forces acting on the cylinder could be measured directly. The mean and root-mean-square (r.m.s.) values of the drag coefficient C_D ($= F_D/0.5\rho U^2 S = F_D/0.5\rho U^2 S$, where ρ is fluid density, U is the towing speed, and S is the projected frontal area) and lift coefficient C_L ($= F_L/0.5\rho U^2 S = F_L/0.5\rho U^2 S$) were computed from the forces measured during the experiments.