Applied Ocean Research 43 (2013) 21–26

Contents lists available at ScienceDirect

Applied Ocean Research

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

Hydrodynamic coefficients of two fixed circular cylinders fitted with helical strakes at various staggered and tandem arrangements

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ARTICLE INFO

Article history:
Received 29 July 2011
Received in revised form 3 June 2013
Accepted 11 June 2013

Keywords:
Strakes
Circular cylinder
Vortex-induced vibration (VIV)
Cylinder interference

ABSTRACT

Experimental results are presented in the paper of two identical stationary cylinders fitted with triple-starting helical strakes subjected to steady uniform cross flows in a flume. The two cylinders were placed at various staggered and tandem positions. In total, 32 relative positions were tested with the streamwise spacing varied 2 to 15 diameters and the transverse spacing from 0 to 7.5 diameters. The hydrodynamic loading was measured in both the in-line and the cross-flow directions for each cylinder. The nominal Reynolds number, based on the cylinder diameter, ranged from 1.40×10^4 to 4.21×10^4. It is found that, as expected, the straked cylinder has a higher drag coefficient in comparison with its smooth counterpart. Qualitatively, the interaction between the two straked cylinders is similar to that between two smooth cylinders in terms of the mean hydrodynamic coefficients. It is further found that whilst the strakes reduce the fluctuating forces on the upstream cylinder, the reduction is significantly smaller for the down-stream straked cylinder.

1. Introduction

Vortex induced vibration (VIV) of marine risers in deepwater is perhaps one of the most challenging topics in offshore engineering. There has been a plethora of technical papers on this specific and complex aspect of riser design over the past two decades [1–4]. However, in spite of this heavy research effort, a high level of uncertainty in the marine riser VIV prediction still remains. This is reflected in the continuing publication of a large amount of analytical, numerical, empirical and experimental works on this topic, as well as the currently recommended safety factors applied to this aspect of riser design which are significantly greater than the normal value of safety factors used in offshore engineering design.

Suppression of the VIV is sometimes needed for marine risers, particularly in deepwater with long riser lengths and strong ocean currents, in order to reduce fatigue damage rates and prolong operational life of the riser. This has led to the development of various methods to reduce the magnitude of the periodic and correlated fluctuating lift force resulting from the regular vortex shedding with the aim of lessening or even completely suppressing the ensuing motion. At the present, helical strakes are perhaps the most robust and commonly adopted suppression device [5]. On the other hand, contrary to the popular use of the helical strakes in practice, it appears that a rigorous understanding of its VIV suppression mechanisms, as well as a systematic measurement of its effects on the hydrodynamic coefficients, are still incomplete. These hydrodynamic coefficients include the drag and the inertia coefficients in both the in-line and the cross-flow directions in either steady and/or oscillatory flows in a wide range of KC numbers. Some very basic design questions, for example, how to determine the in-line hydrodynamic coefficients of a cylinder with strakes in steady and/or oscillatory flows and how these coefficients are related to the strake's height, profile and pitch ratio, have not been addressed satisfactorily. On the fundamental mechanism of suppressing VIV by the use of strakes there are only a limited number of papers available in the public domain exploring the flow field around a straked cylinder through either CFD or experimental measurement [6,7]. It is understood that there have been testing programmes on the VIV suppression performance of various strake designs in the last decade, but most of these studies mainly focused upon the laboratory demonstration of the reduction of the VIV amplitude response. Moreover, most of these data remain proprietary.

Deepwater offshore engineering systems often involve clusters of long flexible cylindrical structures running vertically in parallel or nearly in parallel across the water depth. These risers are close to each other in the horizontal planes. Examples include TLP and SPAR vertical risers where in the mean position the typical spacing to diameter ratio is around 15, as well as some hybrid risers where the spacing to diameter ratio may be greater but the spacing to length ratio remains small. In horizontal ocean currents, some risers may therefore be situated in the wake of other upstream risers, and due to the wake shielding effects the riser spacing is reduced in comparison with that without the currents. Risers of different diameters may be used in a same cluster for different operational functions. In these interfering cases, how the straked risers would interact with each other remains an open question. The interaction may be broadly divided into two

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http://dx.doi.org/10.1016/j.apor.2013.06.001

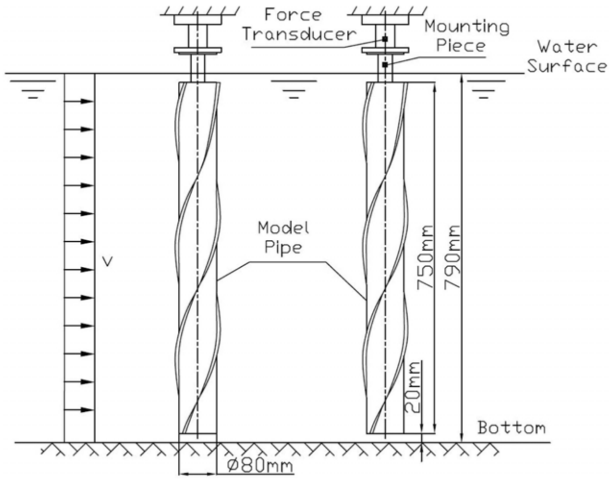

Fig. 1. Schematic of the model test set-up.

Table 1
Spacing between the two cylinders.

X (streamwise distance/D)	Y (transverse distance/D)
0	2.4, 4, 5, 6, 7.5
2	0, 0.5, 1, 1.5, 2
3	0, 0.5, 1, 1.5, 2
4	0, 0.5, 1, 2
5	0, 0.5, 1, 2
7	0, 1.5, 3
10	0, 1.5, 3
15	0, 2, 4

situations, i.e. fixed straked cylinders and flexible straked cylinders. In the former, the key concern is the hydrodynamic coefficients whilst in the latter there are additional complexities such as VIV response and wake induced oscillation [8]. The number of the published studies on the interaction of straked cylinders is very limited. Recently, Korkischko and Meneghini [9] investigated the wake effect on the strake VIV suppression efficiency with an experimental arrangement of two cylinders in tandem. It was found that when the downstream flexible straked cylinder is immersed in the wake of an upstream fixed plain cylinder, it loses its effectiveness significantly compared with the isolated case. The CFD results of two flexible straked risers [10] have also shown that the upstream riser had very little motion whereas the downstream riser had motions several times higher than the upstream.

In the present study, the focus is on the effects of the interaction between closely placed straked cylinders in cross flow on the hydrodynamic coefficients. Two fixed rigid cylinders were subjected to steady uniform cross flows in a flume. The two cylinders were straked and placed at various side-by-side, staggered, as well as tandem arrangements. On each cylinder, the hydrodynamic forces in both the in-line and the cross-flow directions were measured and analysed. In total, 32 relative positions were tested with the streamwise spacing varied 2 to 15 diameters and the transverse spacing from 0 to 7.5 diameters. The nominal Reynolds number, based on the cylinder diameter, ranged from 1.40×10^4 to 4.21×10^4. It is found that, as expected, the straked cylinder has a higher drag coefficient in comparison with its smooth counterpart. Qualitatively, the interaction between the two straked cylinders is similar to that between two smooth cylinders in terms of the mean hydrodynamic coefficients. It is further found that whilst the strakes reduce the fluctuating forces on the upstream cylinder, the reduction is significantly smaller for the down-stream straked cylinder.

2. Model test set-up

A series of tests were carried out at the Danish Hydraulic Institute involving a pair of rigid cylinders of an identical diameter fitted with strakes. The tests were carried out in a current flume. The model test set-up is illustrated in Fig. 1. The flume is 35 m long and 3 m wide with a water depth of 0.79 m. The maximum flow velocity is around 0.7 m/s and the tests were carried out for the mean inflow velocities at 0.2, 0.4 and 0.6 m/s. The turbulence intensity, *Ti*, of the inflow is relatively high. Typically, *Ti* is around 3.8% for the mean inflow velocity at 0.4 m/s. The turbulence intensity is defined as the standard deviation of the in-flow velocity non-dimensionalised by the mean in-flow velocity.

The two cylinders were identical and had a base diameter, i.e. the diameter without taking into account the strake height, of 0.08 m and a length of 0.75 m giving a length to diameter ratio of 9.4. For each cylinder, three identical helical strakes were fitted and the strakes were equally spaced in the circumferential direction. The cross-section profile of the strake is rectangular and the strake height, measured from the cylinder surface, was 0.008 m, i.e. 10% of the cylinder diameter. The pitch of the strakes was 0.8 m, i.e. the pitch ratio was 10. As illustrated in Fig. 1, the model cylinder was placed vertically in the flume with its bottom end 0.02 m above the flume bottom and its upper end below the mean water surface for the same distance. The centre-to-centre distance of the two cylinders can be adjusted in both the in-line and the cross-flow directions. The model cylinders were manufactured in aluminium and the surface of the cylinder was regarded as hydrodynamically smooth. The cylinder upper end was attached to a two-component force transducer for measuring the in-line and the cross-flow forces on the cylinder. The force components were sampled at a frequency of 40 Hz and stored in digital format.

3. Results and discussion

The two cylinder models were placed at various positions relative to each other with respect to the flow direction, including side-by-side, tandem and staggered arrangements. These relative positions, defined by the in-line and cross-flow centre-to-centre distances non-dimensionlised by the use of the cylinder diameter, are given in Table 1. In total, there were 32 positions investigated. For the majority of the relative positions of the two cylinders, tests were carried out for three free-stream velocities at 0.2, 0.4 and 0.6 m/s. The Reynolds numbers, *Rn*, which is based upon the cylinder base diameter, are equal to 14,022, 28,044 and 42,067, respectively.

The hydrodynamic forces, i.e. the drag and the lift on the whole cylinder, are expressed in terms of the non-dimensional coefficients C_d and C_l. These two coefficients are based on the conventional definition, i.e.

$$(C_d, C_l) = \frac{(\text{drag, lift})}{0.5 \times \rho \times D \times L \times V^2}$$

where D is the cylinder nominal diameter; L its length; ρ the water density; V the free-stream velocity. Both the mean value and the standard deviation are calculated, respectively, for C_d and C_l.

It should be noted that the cylinder end effects on the hydrodynamic forces were not quantified in the present study. During the model test, some very small surface waves due to the surface-piercing mounting piece and the submerged cylinder were observed. These small surface waves introduce an additional force component on the cylinder, i.e. the wave-making resistance. However, as the mean inflow velocities were relatively low as well as the large length to diameter ratio of the cylinder, i.e. near 10, the effects of the free surface are not expected to be significant to the results presented in the paper. Similarly, it is believed that the end effects at the lower end of the cylinder are also small. At the lower end, the flume bottom serves as an end plate. However, a gap of 2 cm remains between the flume