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Hydrodynamic Coefficients for Array of Tubular Cylinders

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ABSTRACT

Hydrodynamic coefficients for groups of tubular cylinders subjected to regular waves were experimentally investigated in this study. The experiments were carried out at Universiti Teknologi PETRONAS wave tank. The experimental hydrodynamic forces on tubular cylinders were measured using wave force sensors, while the theoretical values were estimated using Morison equation. The effects of neighboring cylinders, spacing between the pipes, wave frequency and wave amplitude on the hydrodynamic coefficients of tubular cylinders were analyzed. In this study, the model cylinders were fixed to the soffit of the wave tank bridge as cantilevered beams. The tubular cylinders covered in this study are 1.23 m long galvanized steel pipes with 34 mm diameter and 2.5 mm wall thickness. The immersed length of the cylinder was 850 mm. The pipes were subjected to regular waves with maximum wave height of 100 mm, and the Keulegan-Carpenter number (KC) varied from 9.25 to 14.97. The obtained inertia and drag coefficients are in fair agreement with API and PTS specifications.

KEY WORDS: Array of cylinders, Hydrodynamic forces, Drag coefficient, Inertia coefficient, Morison equation, Tubular Cylinders.

INTRODUCTION

In offshore oil and gas industry, estimation of hydrodynamic forces on array of tubular cylinders with sufficient accuracy is a complex task, as the group interface, the effects of spacing between the cylinders, shape and arrangement of arrays, and the interference of group effects with fluids are not fully understood. In practice, the hydrodynamic forces on isolated slender tubular cylinders resulting from waves and current are normally estimated using the well-known Morison equation, as it is the only practical method used for engineering purposes (Li, Wang et al. 1993). Although Morison equation is widely accepted and used by designers and consultants, this semi-empirical model does not consider the grouping effects. However, in practice, offshore platforms consist of a group of tubular cylinders such as risers and conductors which are constructed in close proximity with different arrangements, where the neighboring pipes can significantly influence the hydrodynamic responses of a single isolated cylinder. In addition, the design codes of practice such as API (API 2007), ISO (ISO 2007), DNV (Norsok 2007) and PTS (PTS 2012) recommend fixed values for drag and inertia coefficients when estimating the hydrodynamic forces using Morison equation. The selection of appropriate force coefficients for estimating hydrodynamic forces is a very crucial task faced by designers and stakeholders, with large scatter in laboratory results and even more in those derived from field measurement data (Neill and Hinwood 1998). If the hydrodynamic coefficients for groups of tubular cylinders are determined accurately, the corresponding hydrodynamic loadings on these structures can be estimated accurately, and thus, more cost effective and sustainable design can be achieved.

Estimation of hydrodynamic forces on isolated slender cylinders is not new, as the pioneering research on this topic was conducted by Morison (Morison, Johnson et al. 1950). Later, extensive laboratory research was carried out by Sarpkaya (Sarpkaya 1979). In this study, the author correlated the hydrodynamic coefficients of smooth cylinder with Reynolds number (Re) and Keulegan-Carpenter number (KC). Further, Chakrabarti (Chakrabarti 1981) conducted a similar study in the wave basin to determine the hydrodynamic coefficients of a vertical cylinder and the results were compared with the findings presented by (Sarpkaya 1979). Additional materials pertaining to this topic can be found in (Sarpkaya 1986), (Justesen 1989) and (Bryndum, Jacobsen et al. 1992). In addition, the effects of vortex induced vibration and flow separation characteristics for steady and oscillating flow have been investigated by (Schlichting and Gersten 2000).

Williamson (Williamson 1996) studied the influence of grouping on the force characteristics of pairs of vertical surface-piercing cylinders and suggested that drag and inertia coefficients are dependent on relative spacing between the piles and Keulegan-Carpenter number. However, as on now, only very limited studies have addressed the determination of hydrodynamic coefficients for groups of tubular cylinders. For instance, the interaction of waves with groups of vertical cylinders was investigated by (Chakrabarti 1978), (Chakrabarti 1979) and (Chakrabarti 1981). Additional investations on the topic were reported by (Apelt and Piorewicz 1986), (Li, Wang et al. 1993) and (Smith and Haritos 1997). Recent experimental investigations were carried out by (Sparboom and Oumeraci 2006), (Hildebrandt, Sparboom et al. 2008) and (Bonakdar and Oumeraci 2012). However, none of these studies have investigated the hydrodynamic coefficients for group of cylinders in which wave forces in all the pipes in all different configurations were measured by force sensors. Hence, this study is intended to determine accurate hydrodynamic coefficients for group of tubular cylinders, with more emphasis on the effects of neighboring cylinders, spacing between the pipes on hydrodynamic coefficients. In offshore engineering, jacket platforms, risers, conductors, bridges and piers are generally built up by means of array of tubular cylinders in different configurations and hence, the findings of this study can be used for accurate estimation of hydrodynamic forces on these structures.

THEORETICAL CONSIDERATIONS

Calculation of Hydrodynamic Forces

In offshore engineering, the determination of accurate hydrodynamic forces exerted on structures by the fluid is a cumbersome task. Morison equation is generally used for estimating the external viscous hydrodynamic forces on tubular cylinders subjected to waves (Morison, Johnson et al. 1950). Morison equation was developed assuming that the total in-line hydrodynamic force on a tubular cylinder consists of inertia and drag forces added linearly. The inertia force is developed as the water moving in a wave carries a momentum with it, while the drag force component is caused due to the presence of wake region on the streamside of the cylinder (Chakrabarti 1987). The total hydrodynamic forces over the full water depth due to drag and inertia can be estimated using Equation 1.

$$F = \int_0^d f ds = \int_0^d [C_m \frac{\rho\pi D^2}{4}\frac{du}{dt} + C_d \frac{\rho D}{2}|u+u_c|(u+u_c)]\mathrm{ds} \qquad (1)$$

where d is the water depth , C_m and C_d are the hydrodynamic inertia and drag coefficients, ρ is the water density, D is the pipe diameter, u is the horizontal water particle's velocity, u_c is the current velocity, du/dt is the water particles acceleration, and ds indicates that the integration is done over the full wetted length of the cylinder. The linear Airy wave theory gives the horizontal water particle velocity and acceleration as:

$$u = \frac{\partial\Phi}{\partial x} = \frac{\pi H \cosh ks}{T \sinh kd}\cos\theta \qquad (2)$$

and

$$\dot{u} = \frac{\partial u}{\partial t} = \frac{2\pi^2 H \cosh ks}{T^2 \sinh kd}\sin\theta \qquad (3)$$

where H is the wave height, T is the wave period, $s = d+y$ is the vertical distance from seabed, and the phase angle $\theta = ks - \omega t$. This will give the total hydrodynamic force on the cylinder as:

$$F = \rho g V(\frac{H}{2d})\tanh kd$$
$$\times[C_m \sin\theta + C_d(\frac{H}{4\pi D})\frac{2kd+\sinh 2kd}{\sinh kd}|\cos\theta|\cos\theta] \qquad (4)$$

where V is the volume of displaced water = $\pi D^2 d/4$.

Estimation of Hydrodynamic Coefficients

The hydrodynamic forces on a tubular cylinder change with respect to varying flow kinematics which change with wave height *(H)*, wave period *(T)*, and water depth *(d)*. In this study, the values of drag and inertia coefficients were determined by substituting the measured hydrodynamic forces in Equation 1, and estimating the wave kinematics using airy wave's theory. As the values of C_m and C_d are functions of the phase angle, the best combination of C_m and C_d that satisfy the non-dimensional force $F/\rho g V(H/2d)\tanh(kd)$ and the corresponding phase angles derived from Equation 4 have been selected as the optimum drag and inertia coefficients for each loading cases. Wave kinematics used in Morison equations were estimated using Airy wave theory, in which the wave height $H_{\max}$ is the actual wave height generated in the wave tank, and recoded using wave probes.

EXPERIMENTAL MODEL SET-UP

Fig. 1 shows the model set up in the wave tank. The model consists of a group of vertical tubular cylinders, made of galvanized steel, fixed at the top, to form cantilevered beams. All the pipes used in this study have a total length of 1.32 m, outer diameter D_o = 34 mm, and a wall thickness t = 2.5 mm. Initially, a single pipe was tested in the wave tank, then the number of pipes were increased to form a linear array of 4 pipes, with center to center spacing $S_x=3D$ as depicted in Fig. 2. Then, the model was modified to form a rectangular array of eight by two, with horizontal center to center spacing S_x varying as 3D, 4D and 5D as shown in Figs. 3-5. The model was subjected to regular waves with different wave heights and wave frequencies. The wave forces were recorded using force sensors designed and fabricated by the research group. All the pipes were fitted with wave forces sensors (Idichandy 2001). The model was placed at the center of the wave tank, approximately at a distance of 10 m from the wave maker and the wave absorber. The physical properties of the model and the scaled up prototype details are shown in Table 1.

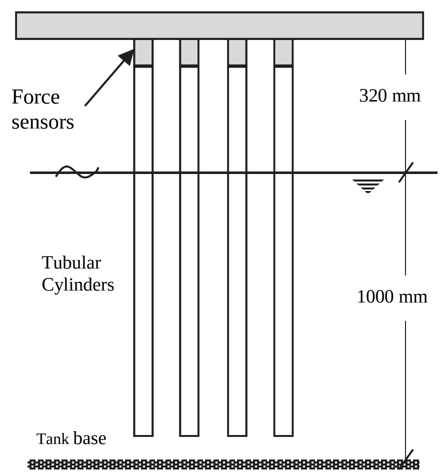

Fig. 1. Details of the model setup in the wave basin

Experimental Program

The model experiments were carried out in the wave basin of Universiti Teknologi PETRONAS, Malaysia. The wave tank dimensions are 20 m by 10 m, with a maximum water depth of 1 m. In this study, regular waves were generated with maximum wave heights H_{max} ranging from 20 mm to 200 mm, and the corresponding tank wave periods varied from 0.6 s to 3.25 s. The wave-maker was controlled through an integrated remote control software package capable of generating regular, irregular and multidirectional waves, while the wave profiles were recorded using four wave probes placed at the vicinity of the model. Details of wave characteristics generated in the wave tank and he corresponding full scale prototype wave data are depicted in Table 2.

Table 1. Physical properties of the model and the scaled up prototype dimensions

Model			Prototype		
Pipe Diameter (m)	Pipe Length (m)	Wall Thickness (m)	Pipe Diameter (m)	Pipe Length (m)	Wall Thickness (m)
0.034	1.23	0.0025	1.87	67.65	0.1375

Table 2. Details of wave characteristics

Model			Prototype			
Wave Period (s)	Frequency (Hz)	H_{max} (m)	Wave Period (S)	Frequency (Hz)	H_{max} (m)	KC
1	1.000	0.1	7.416	0.135	5.5	9.25
1.5	0.667	0.1	11.124	0.090	5.5	9.69
2	0.500	0.1	14.83	0.067	5.5	11.07
2.5	0.400	0.1	18.540	0.054	5.5	12.93
3	0.333	0.1	22.249	0.045	5.5	14.97

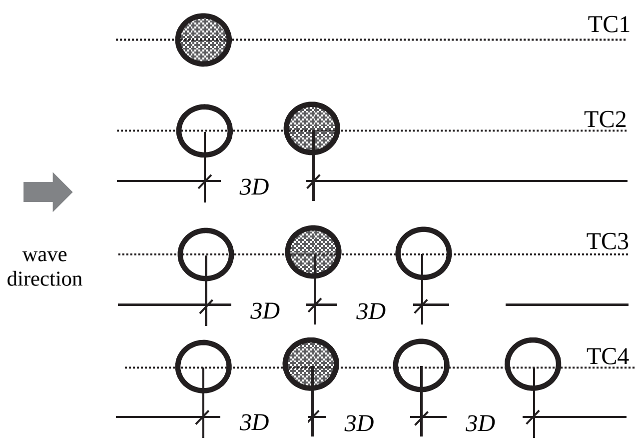

Fig. 2. Different test configurations for array of tubular cylinders in tandem arrangement

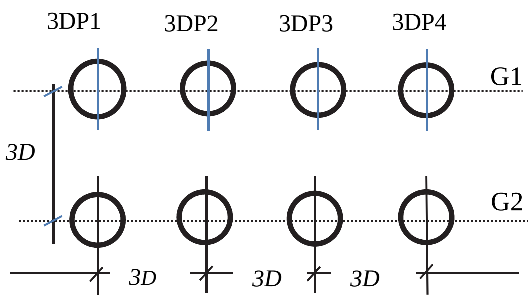

Fig. 3. Model configurations for rectangular arrays, with center to center spacing S_x = 3D

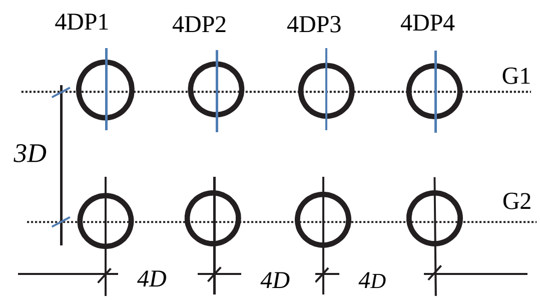

Fig. 4. Model configurations for rectangular arrays, with center to center spacing S_x = 4D

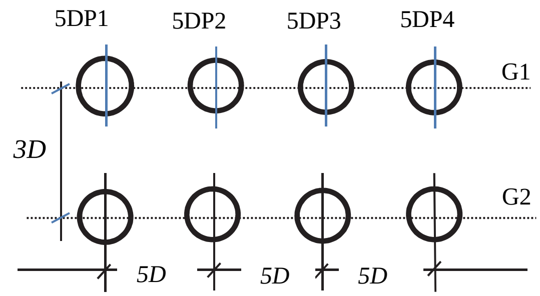

Fig. 5. Model configurations for rectangular arrays, with center to center spacing S_x = 5D

RESULTS AND DISCUSSIONS

In the following paragraphs, the effects of neighboring cylinders, as well as the cylinder's grouping effects on hydrodynamic forces and the corresponding drag and inertia coefficients are discussed.

Effects of Neighboring Cylinders on Hydrodynamic Forces

In this section, comparisons of maximum forces on a tubular cylinder at different configurations are discussed. The tests were conducted to quantify the effects of neighboring cylinders on the hydrodynamic forces of a tubular cylinder with outer diameter D_o = 1.87 m. The cylinder was subjected to regular waves with H_{max} = 5.5 m and time period T varied from 7.42 s to 22.25 s. The measured maximum hydrodynamic forces were analyzed in terms of Keulegan–Carpenter number which can be estimated using Equation 5.

$$KC = \frac{U_{max} T}{D} \tag{5}$$

KC number was selected to compare the test results as it is a function of wave period (T), the maximum flow velocity (Umax) and the pipe diameter (D). Although all the cylinder forces were measured, only the force responses of the highlighted cylinder in Fig. 2 was analyzed and reported for the case of array of cylinders in tandem arrangement, while the responses of all the pipes were analyzed for the group of rectangular arrays with eight cylinders. Initially, a single pipe was tested, and then, the effects of neighboring pipes, as well as the effects of spacing between the pipes on drag and inertia coefficients were investigated experimentally. The maximum force adopted in this study for the comparison of results is defined as the average of representative force heights i.e. trough to crest height (see Fig. 13). In addition, in order to avoid the effects of reflected waves, only the data which were recorded from the time the generated wave hits the model and before the reflected wave reaches the model were considered for the analysis. Fig. 6 shows the hydrodynamic forces of tubular cylinders in different configurations. Here, it can be observed that the effects of Keulegan-Carpenter number on the scaled up prototype force responses are obvious. Regarding the effects of neighboring cylinders, Fig. 6 shows that when an individual pipe was tested as presented in test configuration TC1 (Fig. 2), the maximum force observed was 98175 N, corresponding to KC = 9.24. However, after introducing another pipe to the upstream side of the initial cylinder as depicted in configuration TC2, the maximum measured force was 97791 N, at KC = 9.25 showing a slight decrease of 0.4% on the maximum hydrodynamic forces. Similarly, for test configuration TC3, the maximum forces was 94221 N observed at KC = 11.07 showing a decrease of 4%, while for test configuration TC4, the maximum force observed was 95792 N corresponding to KC = 11.07 showing an overall decrease of 2.43 % as compared to TC1.
However, in order to quantify the effects of neighboring cylinders on, the measured forces in a more systematic manner, the measured hydrodynamic forces should be analyzed on the basis of KC number being the same for all the test configurations. Hence, KC = 11.07 was selected for the comparison, as at this KC number, the recorded forces for all the configurations almost have the same pattern as depicted in Fig. 6. Hence at KC = 11.07, the maximum forces measured for the different configurations are TC1= 80166.7 N, TC2 = 70459.9 N, TC3 = 94221.4 N and TC4 = 95791.7 N. This clearly shows that introducing a pipe on the upstream side of an existing one as in test configuration TC2 has increased the maximum hydrodynamic force of the existing cylinder by 12 %. For test configuration TC3, where one cylinder each was introduced at both the upstream and downstream sides of the existing pipe, the maximum measured force decreased by 17.5%, while for test configuration TC4, the findings suggest an overall decrease of 19.5% on the maximum measured force.
From the above analysis, it can be concluded that introducing neighboring pipes has influenced the maximum hydrodynamic responses of the existing cylinder, although (Bonakdar and Oumeraci 2012) reported that for tandem arrangements, no measurable sheltering effects was noticed for clear spacing of 1D to 3D between the cylinders, which correspond to center to center spacing between the cylinders of S_x = 2D to 4D. However, it is important to mention here that increasing KC number has decreased the maximum measured forces. The effect of neighboring cylinders does not follow the same pattern at various KC numbers as presented in Fig 6.

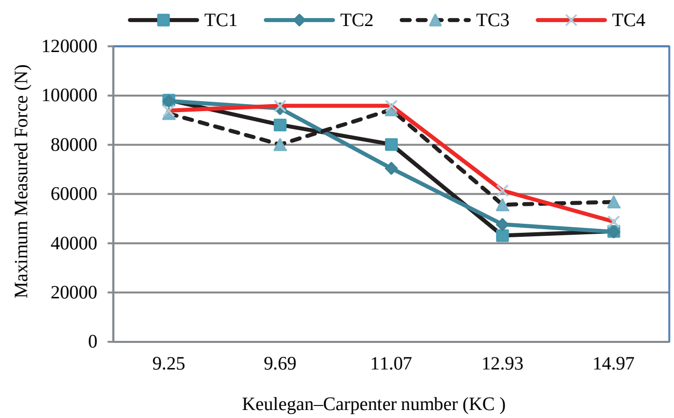

Fig. 6. Comparison showing the variation of maximum hydrodynamic forces on a tubular cylinder due to the effects of cylinder proximity presented versus KC number

Effects of Neighboring Cylinders on Cm and Cd Values

Fig. 7 shows the comparison of drag coefficients for a tubular cylinder with outer diameter Do = 1.87 m at different test configurations analyzed in term of KC number. For configuration TC1 (Fig. 2), where a single pipe was tested, the maximum drag coefficient was Cd = 0.52, corresponding to KC =. 9.24. For configuration TC2, the corresponding maximum drag coefficient was 0.53 at KC = 9.7 showing an increase of 1.5% as compared to TC1. Similarly, drag coefficients for configuration TC3 and TC4 were determined, with the maximum drag coefficients estimated as 0.61 and 0.56 at KC = 11.07 and 9.25 respectively. Here, it can be observed that drag coefficient for TC4 increased by 17%, while for test configuration TC4, the increase in drag coefficient was only 7.7% as compared to the initial test configuration TC1.
Further, in order to establish a more systematic method for estimating the effects of neighboring cylinders on the hydrodynamic coefficients, the drag coefficients for all the test configurations were analyzed at KC =11.07. In this case, the test results show that for TC1, the drag coefficients was Cd = 0.51, while for configuration TC2, the drag coefficient was determined as Cd = 0.45, showing a decrease of -11.8%. However, for test configurations TC3 and TC4, the corresponding drag coefficients were Cd = 0.61 and Cd = 0.55 respectively, with an overall increase of 19.6% and 7.8% respectively as compared to test configuration TC1 (Fig. 2).
Fig. 8 shows the inertia coefficients for the same model test. Here, it can be observed that for configuration TC1 and TC2, the maximum inertia coefficients were determined as Cm = 1.28 and 1.30 respectively, both estimated at KC = 9.25, showing an increase of 1.4%. For test configuration TC3 and TC4, the maximum inertia coefficients were 1.55 and 1.5 respectively, both corresponding to KC=

11.07, showing a decrease of 20% and 17% respectively as compared to TC1. On the other hand, the inertia coefficients for all the test configurations in tandem arrangement as depicted in Fig. 2 were analyzed for KC number being the same for all the tests i.e. KC =11.07. In this case, the inertia coefficient for TC1 was *Cm* = 1.26, while for test configuration TC2, the inertia coefficient was determined as Cm = 1.11, with a decrease of 11.8%. However, for the test configurations TC3 and TC4, an overall increase of 22.7% and 18.7% respectively was observed as compared to TC1.

Generally, the comparison of hydrodynamic coefficients for array of tubular cylinders in tandem arrangement as depicted in Figs. 7-8 revealed that there is a trend showing the variation of hydrodynamic coefficients in term of KC number. However, the drag and inertia coefficients for all the test configurations at various KC numbers do not show the same pattern. Moreover, though the ranges of inertia coefficients presented in this study are in good agreement with the limits specified in API (API 2007), PTS (PTS 2012) and findings reported by Chakrabarti (Chakrabarti 1987) for smooth individual cylinders, the values of drag coefficients are smaller, probably due to the effects of cylinder proximity and sheltering. These preliminary findings together with the results of ongoing analysis for other test configurations can be used to develop a semi-empirical model to predict the hydrodynamic coefficients for group of tubular cylinders, with similar configurations more accurately.

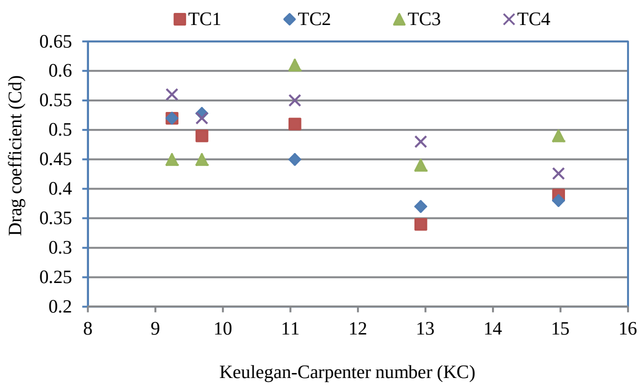

Fig. 7. Comparison showing the variation of drag coefficients for a tubular cylinder with outer diameter D_o = 1.87 m, with different test configurations as a function of KC number

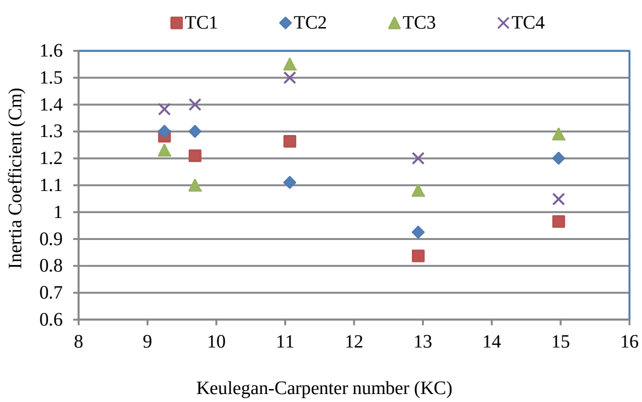

Fig. 8. Comparison showing the variation of inertia coefficients for a tubular cylinder with outer diameter D_o = 1.87 m, with different test configurations as a function of KC number

Grouping Effects on Hydrodynamic Forces

Figs. 9-11, show the comparison of hydrodynamic forces for arrays of tubular cylinders with different configurations, at different KC numbers. The model was tested with a fixed lateral spacing $S_y = 3D$, while the center to center spacing along the wave direction was varied as S_x = 3D, 4D, and 5D. Although, each of the model arrangement shown in Figs 3-5 consists of eight cylinders, only the hydrodynamic responses for group 1 (G1) are reported in this paper, due to the symmetrical geometry of the model set up. Figs. 9-11 show that the maximum hydrodynamic forces for all the pipes at different configurations follow the same pattern, with the peak forces recorded at KC = 11.07, while the minimum force responses were observed at KC = 14.97. For test configuration with S_x = 3D (Fig. 3), the maximum force recorded was 116229 N corresponding to cylinder 3DP3 observed at KC = 11.07 as shown in Fig. 9. When the spacing was increased to S_x = 4D (Fig. 4), the maximum hydrodynamic force was 113764 N for cylinder 4DP1 recorded at KC = 11.07. However, as depicted in Fig. 10, for test configuration with S_x = 5D (Fig. 5), the analysis of the result shows that the maximum hydrodynamic force was 121235 N recorded at KC = 9.68, corresponding to cylinder 5DP1. For a better comparison of the results, KC = 11.07 was adopted for comparison of the grouping effects.

Fig. 9 shows the variation of maximum forces for array of tubular cylinders, with center to center spacing, $S_x = 3D$ (Fig. 3). Here, at KC = 11.07, it can be observed that the maximum recorded forces for the different cylinders are 3DP1 = 111773 N, 3DP2 = 87876 N, 3DP3 = 116229 N and 3DP4 = 102144 N. However, when the center to center spacing between the pipes along the wave direction was increased to, S_x = 4D (Fig. 4), while keeping the KC number constant, at KC = 11.07, the test results suggest that the maximum hydrodynamic forces for 4DP1=113764 N, 4DP2 = 91219 N, 4DP3 = 91627 N and 4DP4 = 93864 N as depicted in Fig. 10. Here, it can be observed that changing the center to center spacing between the pipes from $S_x = 3D$ to $S_x = 4D$ has influenced the magnitude of hydrodynamic forces on each cylinder. For instance, reductions of 1.8 % and 3.8% were observed for cylinders 4DP1 and 4DP2 respectively, while the results show an overall increase of 21.2% and 8.1% for 4DP3 and 4DP4 respectively. Later, the center to center spacing between the cylinder was set to S_x = 5D (Fig. 5) and the forces on the different cylinders were measured and analyzed. Here, as depicted in Fig. 11, the measured hydrodynamic forces at KC = 11.07 for the different cylinders are 5DP1 = 121235 N, 5DP2 =112816 N, 5DP3 =112632 N and 5DP4 = 101132 N. By a simple comparison of these findings with the initial case where S_x = 3D, it is obvious that an overall decrease of 8.5% and 28.4 % were observed on the maximum measured forces for cylinders 5DP1 and 5DP2 respectively, while for cylinders 5DP3 and 5DP4, the results showed an overall increase of 3% and 1% respectively on the maximum measured forces.

Generally, it can be observed that increasing KC number has decreased the measured force responses. The analysis of the results also shows that the spacing between the cylinders has influenced the measured forces on each cylinder; however this influence does not follow a fixed pattern as discussed in the previous paragraphs. However, this paper is only presenting a part of ongoing experimental study. It is expected that by combining all the results for different cylinder diameters, tested for different wave heights and different wave frequencies; it will be possible to establish a regression equation. Besides, in this study, the minimum center to spacing adopted for experimental investigation was S_x = 3D. Hence, to achieve much better results, further investigation with horizontal spacing S_x < 2D might be required.

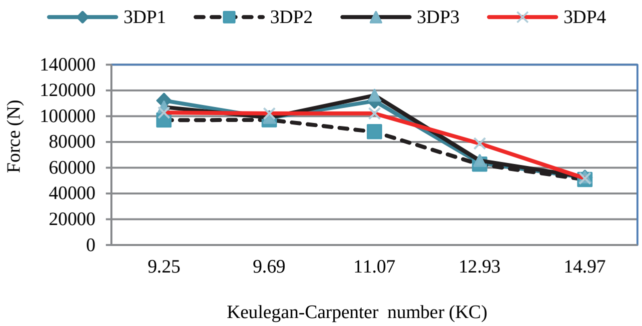

Fig. 9. Comparison of hydrodynamic forces for array of tubular cylinders, with center to center spacing $S_x = 3D$.

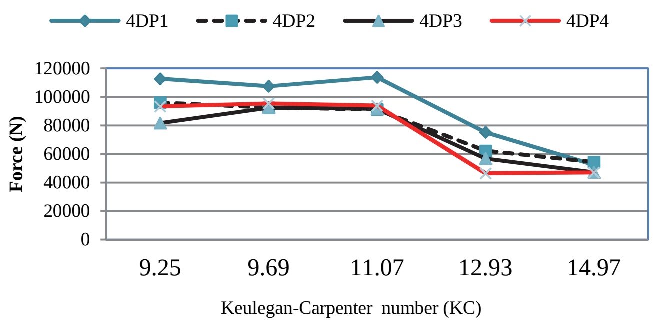

Fig. 10. Comparison of hydrodynamic forces for array of tubular cylinders, with center to center spacing $S_x = 4D$.

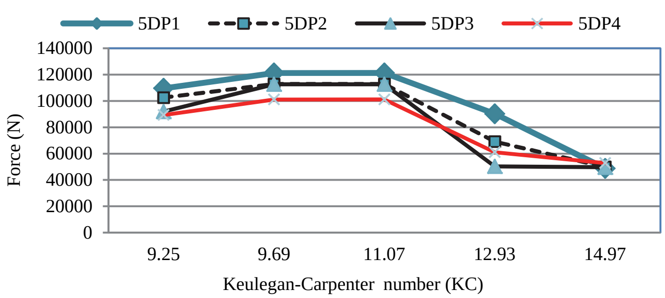

Fig. 11. Comparison of hydrodynamic forces for array of tubular cylinders, with center to center spacing $S_x = 5D$.

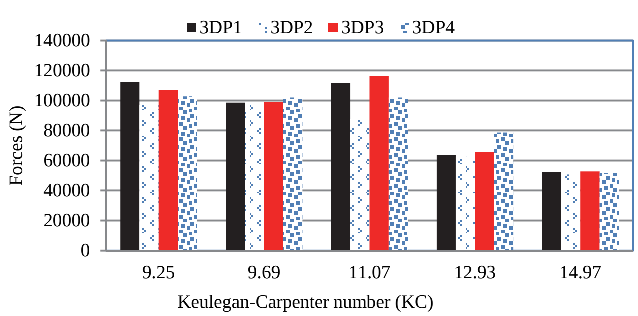

Fig. 12. Comparison of hydrodynamic forces for four tubular cylinders in tandem arrangement, with center to center spacing S_x = 3D, for different KC numbers

Fig. 12 shows the variation of hydrodynamic forces on all the four pipes of array of cylinders in group G1 (Fig. 3), as a function of KC number. Here, it is obvious that although the four cylinders have the same physical properties, and the center to center spacing along the wave direction was kept constant i.e. S_x = 3D, there is no definite tendency of hydrodynamic responses of the cylinders for a given KC number. For instance, at KC = 9.24, the cylinder 3DP1, which is the leading cylinder showed the maximum hydrodynamic response as 112192 N, followed by the third cylinder 3DP3 with 1071340 N and 3DP4 with 102807 N, showing a difference of 13.5% between the maximum and the minimum force responses. For KC = 9.69, the maximum force was recorded for cylinder 3DP4 as 102116 N, followed by 3DP3 with 116229 N, and 3DP1 and 3DP2 with 111773 N, and 87876 N respectively. Here, it can be seen that the difference between the force responses at this KC number is comparatively very small. Further, for *KC* =11.07, the analysis of the results shows that the maximum force was recorded for cylinder 3DP3 as 116229 N, followed by 3DP1 with 111773 N and 3DP2 and 3DP4 with 102144 N and 87876 N respectively. At this KC number, the overall maximum wave forces were recorded as depicted in Fig. 12. Furthermore, at KC=12.93, the hydrodynamic forces on all the four cylinders were significantly smaller as compared to the previous case i.e. KC =11.07, with the maximum force observed for cylinder 3DP4 as 78794 N, followed by 3DP3 with 65584 N and 3DP1 and 3DP2 with 63810 N and 62670 N respectively. However, for KC =14.97, the analysis of the results revealed that the hydrodynamic response for the four cylinders was around 52767 N.

Generally, recorded data can be analyzed either by statistical analysis or by wave by wave analysis. In this study, wave by wave method was adopted. Hence, the forces corresponding to each wave were individually analyzed and the results were compared. However, to determine the accurate phase angle θ that satisfies Equation 4 and corresponds to the optimum C_m and C_d values, the measured force amplitude of one cycle was considered for each load case. This cycle was taken as the average of a number of cycles of stabilized force responses. Then, by substituting the measured forces in the left hand side of Equation 4, and the theoretically estimated forces in the right hand side, the non-dimensional form of the force responses can be determined by dividing the measured forces by the theoretically estimated values. Then, drag and inertia coefficients that satisfy both the phase angles depicted in Fig. 13 and the non-dimensional forces at peaks and zero crossing points of the representative force cycle were adopted as the optimum hydrodynamic coefficients for each loading case.

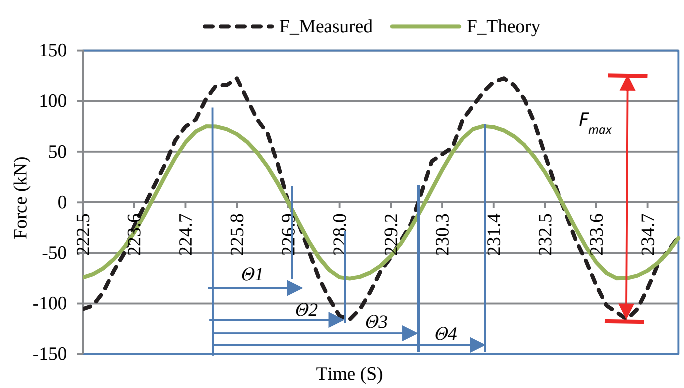

Fig. 13. Schematic diagram showing the measured and theoretically estimated hydrodynamic forces and the phase angles adopted for determination of *Cm* and *Cd* values

Grouping Effects on Hydrodynamic Coefficients

Fig. 14 shows comparison of drag coefficients for a group of tubular cylinders, with different center to center spacing versus KC number. It is clear that the values of hydrodynamic coefficients for cylinders with different configurations are influenced by KC number. For instance, for configuration with S_x = 3D, the test results show that values of drag coefficients vary from C_d = 0.44 to 0.75, with the maximum value recorded for cylinder 3DP3 (Fig. 3), at KC = 9.68. Further, for the test configuration with S_x = 4D, the analysis of the results shows that the maximum drag coefficient was C_d = 0.75 corresponding to cylinder 4DP1 (Fig. 4), at KC = 9.68, whilst the minimum drag coefficient was determined as 0.40, corresponding to the forces response of cylinder 4DP2, at *KC* = 14.97. In addition, for configuration with S_x = 5D, the determined drag coefficients were found to be varying from C_d = 0.426 to 0.80 both corresponding to 5DP1esimated at KC = 14.97 and 11.07 respectively.

The effects of grouping with varying center to center spacing on drag coefficients were also investigated at KC = 11.07. In this case for configuration with S_x = 3D, the drag coefficients for the different cylinder were determined as 3DP1 with C_d = 0.55, and 3DP2 with C_d = 0.54, and 3DP3 and 3DP4 with C_d = 0.55 and 0.45 respectively. Similarly, the drag coefficients for S_x = 4D were analyzed at KC = 11.07, with 4DP1 and 4DP2 having drag coefficient of C_d = 0.6 and 0.45 and 4DP3 and 4DP4 with C_d = 0.52 and 0.53 respectively. In this configuration, it seems evident that the drag coefficient for 4DP1, 4DP2, and 4DP3 decreased by 18.18%, 16.67% and 5.45% respectively, while for 4DP4, an increase of 17.78% was noticed as compared to tests configuration with S_x = 3D. Further, the comparison of drag coefficient for S_x = 5D suggests that 5DP1 and 5DP2 have drag coefficients as C_d = 0.8, and 0.45 respectively, while for 5DP3 and 5DP4, the corresponding drag coefficient are C_d = 0.79 and 0.72, here, the drag coefficient for 5DP1 was increased by 45%, followed by 5DP2 with a decrease of 16.7%, while 5DP3 and 5DP4 both have shown an increment of 43.6% and 59.8% respectively on their drag coefficients as compared to test configuration with S_x = 3D.

Similarly, Fig. 15 shows the relation between the inertia coefficients and the cylinder grouping and the center to center spacing effects presented versus KC number. For configuration with S_x= 3D (Fig. 3), the analysis of the results shows that the inertia coefficients vary with respect to KC number as well as with respect to the configuration of model arrangement. Here, the minimum inertia coefficient was estimated as C_m = 1.1 for cylinder 3DP4 at KC = 11.07, whilst the maximum value was determined as C_m = 1.90, for the same cylinder but corresponding to KC = 9.69. Furthermore, when the maximum horizontal spacing of array of tubular cylinders was set as S_x = 4D, the minimum and maximum inertia coefficient were C_m = 1 and 1.84 respectively. The minimum value corresponds to cylinder 4DP4 (Fig. 4) determined at KC = 14.97, while the maximum value corresponds to cylinder 4DP1 determined for KC = 9.69. For configuration, with S_x= *5D* (Fig. 5), the analysis of the results revealed that the minimum and maximum values for inertia coefficients were 1.04 and 1.98 respectively, both corresponding to cylinder 5DP1 and recorded at KC = 11.07 and 14.97 respectively.

The comparison of inertia coefficients at KC = 11.07, shows that for configuration with S_x = 3D, the estimated inertia coefficients for the different cylinders are 3DP1 with C_m = 1.35, 3PD2, with C_m =1.36, and 3DP4 and 3DP5 have inertia coefficients of 1.38 and 1.1 respectively. However, when the value of S_x was changed from 3D to 4D, the corresponding inertia coefficients for 4DP1 and 4DP2 were 1.55 and 1.1 respectively, while 4DP3 and 4DP5 recorded inertia coefficients of 1.33 and 1.35 respectively. This indicates that inertia coefficient for cylinder 4PD1 has increased by 14.5%, while 4DP2 and 4DP3 have both experienced a decrease of 19% and 3.6% respectively in their inertia coefficients, while the inertia coefficient for 4DP4 increased by 22.7% as compared to the initial condition where S_x = 3D , as depicted in Fig. 15. For test configuration with S_x = 5D, the graphs in Fig.15 suggest that the inertia coefficients for the different cylinders are 5DP1 with C_m = 1.98 and 5DP2 with C_m = 1.1 followed by 5DP3 and 5DP4 with C_m =1.91 and 1.77 respectively. In this configuration, one can observe that the inertia confident for 5DP1 has increased by 46%, while 5DP2 has recorded a decrease of 19% in its inertia coefficient as compared to test configuration with S_x= 3D. Similarly, for cylinder 5DP3 and 5DP4, the analysis of the results shows that the inertia coefficients have increased by 38% and 61% respectively.

In conclusion, one can observe that, increasing the center to center spacing of array of tubular cylinder from 3D to 4D and then to 5D has shown an influence on drag and inertia coefficients when plotted versus *KC* number. However, the variation does not follow the same pattern when the data were analyzed and compared at various KC numbers.

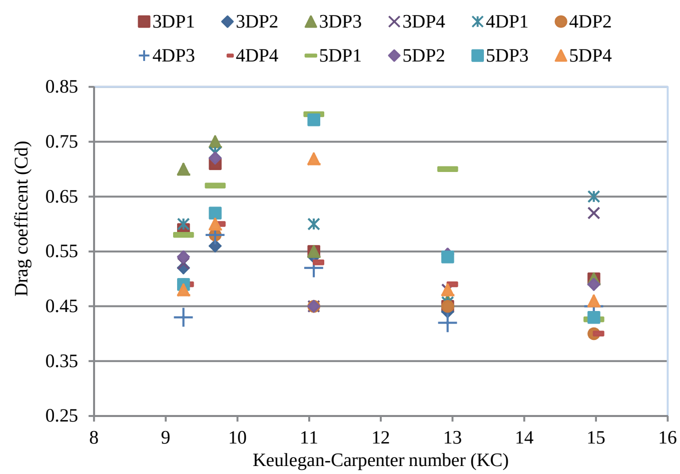

Fig. 14. Comparison of drag coefficients for array of cylinders, with different center to center spacing S_x = 3D, 4D, and 5D as a function of KC number

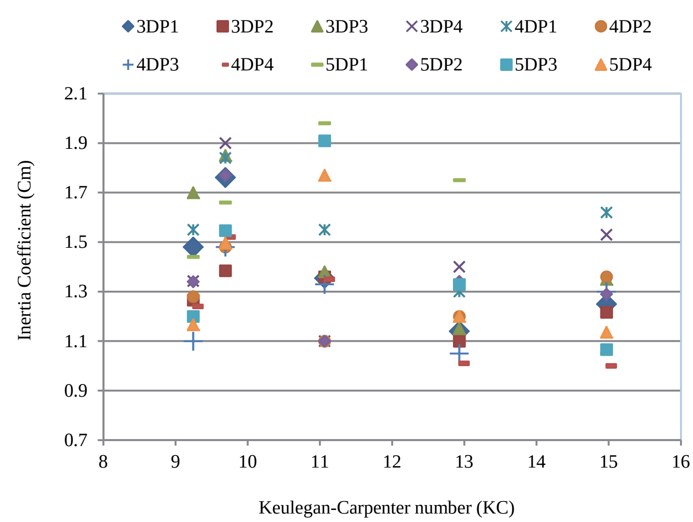

Fig. 15. Comparison of inertia coefficients for array of cylinders, with different center to center spacing S_x = 3D, 4D, and 5D as a function of KC number.

CONCLUDING REMARKS

Experimental investigation was conducted in the wave tank to investigate the effects of neighboring cylinders, Keulegan-Carpenter number, the center to center spacing between the cylinders on the hydrodynamic forces and the corresponding hydrodynamic coefficients. From this study, the following conclusions can be drawn for the full scale prototype:

1. Generally, the comparison of hydrodynamic forces, and force coefficients for array of tubular cylinders in tandem arrangement revealed that there is a trend showing the variation of hydrodynamic forces and the corresponding hydrodynamic coefficients in term of KC number. However, the variation of drag and inertia coefficients for all the test configurations at different KC numbers does not follow the same pattern.

2. Similarly, for group of cylinders with varied center to center spacing between the pipes, it can be observed that increasing *KC* number has decreased the measured force responses. The analysis also shows that the spacing between the cylinders has influenced the measured forces as well as the corresponding hydrodynamic coefficients of each cylinder. However this influence does not follow the same pattern at different KC numbers. It is hoped that by combining all the results, for different cylinder diameters, tested for different wave heights and different wave frequencies; it will be possible to arrive at a regression equation.

3. In this study, the experimental investigation was conducted for a minimum center to center spacing between the pipes S_x = 3D due to limitations in the model set up. Hence, further investigations with horizontal spacing, S_x < 2D might be required for better understanding of the sheltering effects.

4. The inertia coefficients determined for linear arrays of cylinders in tandem arrangement and those determined for group of tubular cylinders with different center to center spacing are in fair agreement with the specified values in API and PTS. In most of the cases, the drag coefficients were found to be smaller than the specified values in API and PTS.

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