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Effect of Anodes on Hydrodynamic Coefficients of Tubular Cylinders - Model Tests

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Abstract. This paper examines the hydrodynamic behavior of a tubular vertical cylinder with anode fittings subjected to regular waves. The model experiments were carried out in the wave basin of Universiti Teknologi PETRONAS. The model was made from galvanized steel, with outer diameter D_o= 0.034 m and total length l = 1.23 m, fixed vertically to the soffit of the wave tank bridge, and the free end was immersed in the wave tank to form a cantilevered beam with wetted length of 0.85 m. Overall, seven anodes were welded to the wetted length of the tubular cylinder, at a center to center spacing of 0.12 m. The model was subjected to regular wave with H_{max} varying from 0.1 m to 0.2 m, with wave height increment of 0.05 m, and the time period varying from T = 1 s to 3 s. The tests were conducted for Keulegan-Carpenter number ranging from 3.9 to 23.3. The hydrodynamic forces and the corresponding hydrodynamic coefficients of the smooth cylinder were compared with the force responses of a tubular cylinder with the same outer diameter, fitted with anodes. A scale factor of 1:55 was adopted in this experimental study based on the limitations of the maximum water depth in the wave tank, and the scaled up force responses of the full scale prototype were analyzed and discussed. The results show that, installation of anodes has increased the drag coefficients by up to 20% depending on the wave frequencies at which the model was tested.

Introduction

Anodes are part of cathodic protection system used in offshore engineering to mitigate corrosions. The cathodic protection is the most cost effective and technically appropriate method adopted for controlling corrosion of offshore platforms [1]. This technique is utilized either alone or in conjunction with protective coatings which is mainly limited to splash zones. The CP system consists of sacrificial anodes, with a design life equal to the expected life of the platform i.e. 20 -30 years. These types of anode are maintenance-free, and positioned in primary bracing and on primary horizontal bracing of offshore platforms. The CP system is capable of polarizing all submerged steel to a potential between -800 mV and -1100 mV [2]. For instance, in Malaysian offshore locations, anodes with 350 mm stand-doff type, made of aluminum, with minimum alloy weight of 350 kg, and approximate anode weight of 440 kg are recommended by PTS [3]. From the structural view point, anodes increase the projected areas of tubular cylinders, and consequently, increase the added mass and the hydrodynamic loadings. Hence, a good understanding of the effect of anodes on hydrodynamic responses of tubular cylinders is important for accurate estimation of hydrodynamic loading on these structures. To accommodate the effects of anodes during the estimation of hydrodynamic forces, the codes of practice normally specify modified coefficients. For tubular smooth cylinders Cm = 1.60 and Cd = 0.65 [4], while the specified values for inertia and drag coefficient for tubular cylinders with anodes are Cm = Cd =2 [3]. The pioneering study on estimation of hydrodynamic coefficient experimentally was conducted by Morison et al.[5]. Much later, Sarpkaya [6] correlated the hydrodynamic coefficients of smooth cylinder with Reynolds number and Keulegan-Carpenter number. In addition, another study was conducted by Chakrabarti [7] to determine the hydrodynamic coefficients of a vertical cylinder in the wave tank, and the findings were compared with those presented by Sarpkaya [6]. Additional materials in this topic can be found in [8-14] where the authors provided comprehensive experimental investigations on hydrodynamic forces and hydrodynamic coefficients of slender cylinders. However, to the author's knowledge, literature that addresses the effect of anodes on hydrodynamic coefficients for Malaysian offshore locations are not available.

Theoretical Background

Estimation of Wave Forces: Morison equation is generally used for estimating the external viscous hydrodynamic forces on tubular cylinders subjected to wave loadings [5]. This equation assumes that the total in-line hydrodynamic force on a tubular cylinder consists of inertia and drag forces added linearly. The total wave force due to drag and inertia can be estimated using Equation 1.

$$F = \rho g V \left(\frac{H}{2d}\right) \tanh kd \times [C_m \sin\theta + C_d \left(\frac{H}{4\pi D}\right) \frac{2kd + \sin sh 2kd}{\sin sh 2kd} |\cos\theta| \cos\theta] \quad (1)$$

where ρ is the water density , V is the volume of displaced water $= \pi D^2 d/4$, H is the wave height, C_m and C_d are the hydrodynamic inertia and drag coefficients respectively and D is the pipe diameter.

Determination of Hydrodynamic Coefficients: The values of drag and inertia coefficients can be determined by substituting the measured hydrodynamic forces in Equation 1, and estimating the wave kinematics using airy waves theory. However, as the values of *Cm* and *Cd* are functions of the phase angle θ, the best combination of *Cm* and *Cd* and the corresponding phase angles that satisfy Equation 1 have been selected as the optimum drag and inertia coefficients for each loading case.

Experimental Details

Wave Tank Details: The model experiments were carried out in the wave basin of Universiti Teknologi PETRONAS (UTP). The wave tank dimensions are 20 m by 10 m with a maximum water depth of 1 m. Regular waves were generated with wave heights ranging from 0.02 m to 0.2 m, for model periods varying 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 around the model. Two wave probes were placed before the model, whilst the remaining two were placed after the model at a center to center spacing of 1.8 m.

Experimental Set up and Procedure: As shown in Figure 1, two vertical rigid cylinders were used in this experimental investigation. The first cylinder is smooth, while the second cylinder was fitted with anodes. Each cylinder was vertically mounted to form a cantilevered beam. One end was fixed to the wave tank bridge to form a rigid cantilevered beam, while the free ends were submerged in the wave tank. The model pipes were made of galvanized steel, with outer diameter D_o= 34 mm and wall thickness t = 2.5 mm. The wave forces were measured using wave force sensors, specially designed and fabricated by the research group in UTP. Detail of the load sensor used in this study was published earlier by Idichandy [15]. The physical properties of the model and the scaled up prototype details are shown in Table 1. The counter balancing moment is eliminated by placing the strain gauges at the locations where the moment is almost negligible.

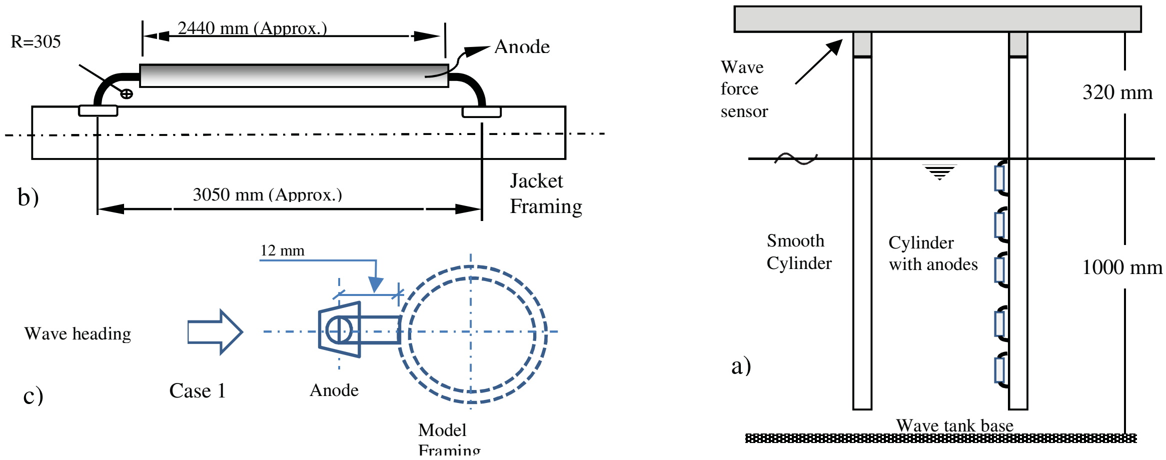

Figure 1: Test models' details: (a) Model set-up in wave tank, (b) Typical anode fixing details, and (c) anode orientation with respect to wave heading

Table 1: Properties of the Model and the Prototype

Model			Prototype		
Pipe Diameter (m)	Pipe Length (m)	Wall Thickness (m)	Pipe Diameter (m)	Pipe Length (m)	Wall Thickness (m)
0.034	1.23	0.0032	1.87	67.65	0.176

Experimental Programme: In order to investigate the effects of anodes on drag and inertia coefficients, an extensive experimental investigation was conducted in the wave tank at UTP. Table 2 depicts the different wave periods and the associated wave frequencies generated in the wave tank during the model test. These wave periods were generated using modal wave heights of 0.2 m, 0.15 m and 0.1 m. as shown in Table 3. The corresponding prototype wave heights are 11 m, 8.25 m and 5.5 m respectively. The hydrodynamic forces and the associated hydrodynamic coefficients for the prototype resulting from these loading conditions were scaled up using a scale factor of 1:55 and the findings are discussed in the following sections.

Table 2: Details of Wave Characteristics Generated in the Wave Tank

Model		Prototye	
Wave Periods (*s*)	Frequency (*Hz*)	Wave Period (*s*)	Frequeny (*Hz*)
1	1	7.416	0.135
1.5	0.667	11.124	0.090
2	0.500	14.83	0.067
2.5	0.400	18.540	0.054
3	0.333	22.249	0.045

Table 3: Details of Wave Heights Generated in the Wave Tank

Model	Prototype
Wave Height (m)	Wave Height (m)
0.2	11
0.15	8.25
0.1	5.5

Experimental Results and Discussion

Hydrodynamic Forces: Figure 2 depicts the hydrodynamic forces for a smooth rigid cylinder with outer diameter of 2.31 m, compared with the force responses of a similar cylinder with the same physical properties, fitted with anodes. The results show that, when the smooth cylinder was subjected to regular wave with H_{max} = 11 m, and wave period T = 14.83 s, the hydrodynamic force was 331.49 kN. However, when anodes were fitted to the smooth cylinder as shown in Figure1, and the test was repeated with the same wave characteristics, the results show that the average hydrodynamic force on the cylinder with anode fittings was 434.92 kN, an increase of 31% on the total hydrodynamic force. This clearly shows that anodes can significantly affect the hydrodynamic performance of tubular cylinders. In addition, while keeping the wave height constant at 11 m, the wave period was increased from T = 14.83 s to 18.54 s, and the forces were measured. As shown in Figure 3, the average hydrodynamic force on the smooth cylinder was 222.42 kN, whilst the corresponding response of the cylinder fitted with anodes was 273.09 kN, an overall increase of 22 % on the total hydrodynamic forces as a result of anode fittings. Here, it can also be observed that although in both the above cases, the number of anodes and wave headings were the same, changing the wave frequencies has considerably influenced the magnitudes of hydrodynamic responses of the prototype.

Similarly, as presented in Figure 4, the wave period was decreased to 11.12 s while the wave height was 11 m, and the hydrodynamic forces were measured. Here, it can be observed that the force reposes of the smooth cylinder was 469.81 kN, while the corresponding hydrodynamic forces on the cylinder fitted with anodes was 398.63 kN, a reduction of 15% on the overall hydrodynamic forces. The reason behind this reduction in the force responses can be associated with the frequency of applied wave at this particular case. However; further investigations need to be conducted in order to explain this phenomenon experimentally.

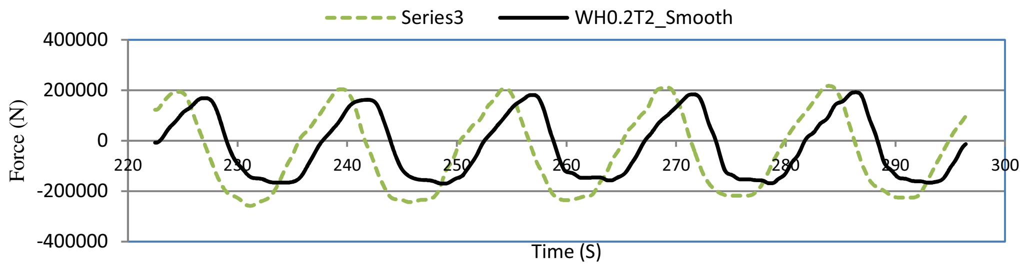

Figure 2: Hydrodynamic Forces for 2.31 m Diameter, Smooth, and Anodes Fitted Cylinders Subjected to Regular Waves with H_{max} = 11 m and T = 14.83 s

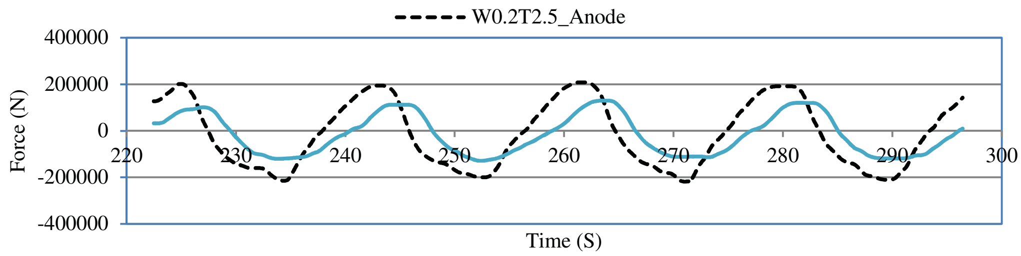

Figure 3: Hydrodynamic Forces for 2.31m Diameter, Smooth, and Anodes Fitted Cylinders Subjected to Regular Waves with H_{max} = 11 m and T = 18.54 s

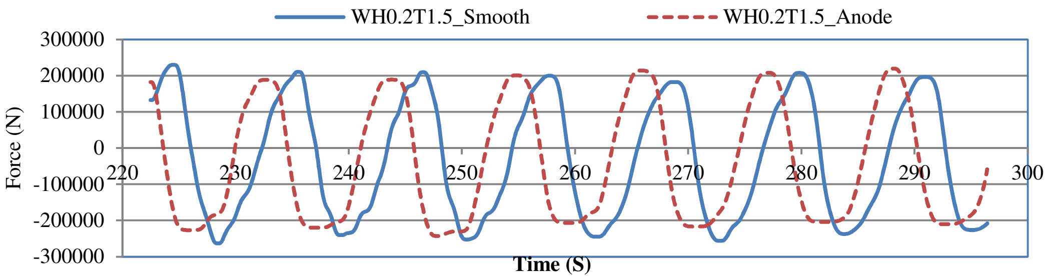

Figure 4: Hydrodynamic Forces for 2.31 m Diameter, Smooth, and Anodes Fitted Cylinders Subjected to Regular Waves with H_{max} = 11 m and T = 11.12 s

Estimation of Hydrodynamic Coefficients: In this section, drag and inertia coefficients for a smooth cylinder, and a similar cylinder fitted with anodes, subjected to regular waves are discussed. The hydrodynamic forces were determined using Morison equation, and *Cm* and *Cd* were determined by equating the measured forces to the theoretical values estimated using the wave kinematics. The hydrodynamic coefficients were determined for different loading conditions as discussed in the following paragraphs.

Figure 5 shows the scaled up inertia coefficients for the full scale prototype smooth cylinder compared with those of a similar cylinder fitted with anodes. Both the cylinders have an outer diameter D_o = 2.31 m, subjected to regular waves with H_{max} =11, 8.25 and 5.5 m, and wave periods varying from T = 11.12 s to 24.1 s. The results show that the minimum inertia coefficient for the smooth cylinder, *Cm* = 1, recorded for H_{max}= 5.5 m and *T* = 18.54 s, while the maximum *Cm* = 2.79 recorded at H_{max}= 11m and *T* = 22.25. The corresponding minimum and maximum *Cm* values for the cylinder fitted with anodes are 0.85 and 2.1 recorded at H_{max} = 8.25 m, *T* = 22.248, and H_{max} =11 m, *T* = 22.24 s respectively.

Similarly, as shown in Figure 6, the drag coefficient for the smooth cylinder was varied from *Cd* = 0.4 to 1.5, with the minimum value observed at H_{max} = 5.5 m and *T* = 14.83 s, the maximum drag coefficient was recorded at H_{max}= 5.5 m and *T* =22.24 s, while the maximum drag coefficient for the cylinder fitted with anodes was *Cd* = 0.6 recorded at H_{max}= 8.25 m and *T* =22.24 s, while the maximum drag coefficient was determined as *Cd* = 1.8 for wave with H_{max}= 11 m and *T* = 22.24 s. Here, it can be observed that anode fittings have increased the drag coefficients up to 20% depending on the wave heights and the frequencies at which the model was tested. The inertia coefficients also have shown some changes due to anode fittings, but these changes remain small as compared to drag coefficients.

Generally, drag and inertia coefficients determined experimentally in this study are in good agreement with the specified ranges in PTS [3] and API [4] as *Cm* = 1.60 and *Cd* = 0.65. The large part of the findings are comparatively smaller than the specified ones, which is encouraging for design of more sustainable and cost effective platforms for Malaysian offshore locations. This indicates that the specified values are more conservative.

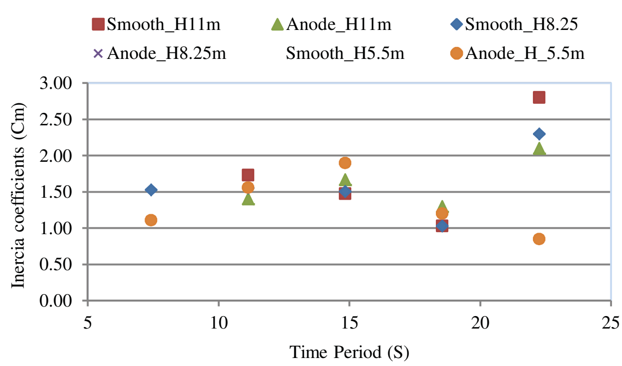

Figure 5: Inertia coefficients for 2.31 m Diameter, Anodes fitted and Smooth Cylinders Subjected to Regular Waves with H_{max} = 11 m

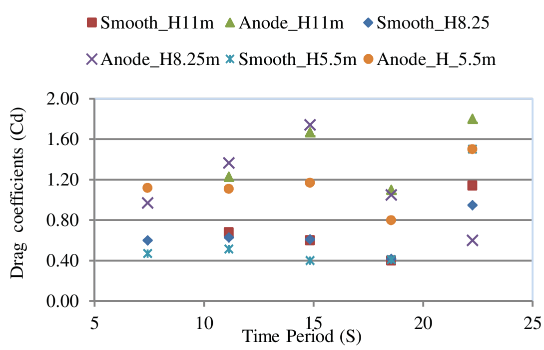

Figure 6: Drag coefficients for 2.31 m Diameter, Anodes fitted and Smooth Cylinders Subjected to Regular Waves with H_{max} = 8.25 m

Conclusions

From the extensive model tests on the effects of anodes on the hydrodynamic forces and on the hydrodynamic coefficients, the following conclusions can be drawn for the scaled up prototype:

1. The experimental results show that installation of anode fittings to a smooth tubular cylinder with outer diameter of 2.31 m has increased its hydrodynamic forces. The influence of

anodes on hydrodynamic forces depending on the wave heights and the wave frequencies at which the model was tested.

2. Generally, anode fittings have modified the geometry of the tubular cylinder, and as a result, the drag coefficients were increased significantly. The effects of anode fittings on inertia coefficients were generally small as compared to drag coefficients. The findings also suggest that drag and inertia coefficients are highly dependent on the wave frequency as well as on the wave heights at which the cylinder was tested.

3. Drag and inertia coefficients determined experimentally in this study are in good agreement with *Cm* and *Cd* values specified by PTS and API. The large part of the findings are comparatively smaller than the specified values, which is encouraging for design of more sustainable and cost effective platforms for Malaysian offshore locations.

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