

## Effect of Sacrificial Anodes and Marine Growth on Hydrodynamic Coefficients of Rigid Cylinders

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### ABSTRACT

Estimation of accurate hydrodynamic coefficients for tubular cylinders fitted with anodes and wrapped with marine growth is a complex task. The interaction of fluid with sacrificial anodes and marine growth surface is not fully understood. The objective of this study is to determine the effect of sacrificial anodes and marine growth on hydrodynamic coefficients of rigid cylinders experimentally. In this study tubular cylinders with outer diameter  $D_o = 42$  mm were tested in the wave tank. The total hydrodynamic forces and the corresponding drag and inertia coefficients were analyzed at different Keulegan Carpenter ( $KC$ ) numbers. The tests were conducted in the offshore engineering laboratory of Universiti Teknologi PETRONAS, Malaysia. In this experimental investigation, a scale factor  $\lambda$  of 1:55 was adopted and all the parameters are analyzed and presented in terms of scaled up prototype values in accordance with Froude scaling law. The test results suggest that the cylinder fitted with sacrificial anodes and the one wrapped with rough surface have shown an overall increase in drag and inertia coefficients.

**KEY WORDS:** Drag coefficient, Hydrodynamic forces, Inertia coefficient, Marine growth, Morison equation, Sacrificial anodes, and Tubular cylinders.

### INTRODUCTION

Estimation of accurate hydrodynamic coefficients for tubular cylinders subjected to hydrodynamic forces is an essential task in offshore structures. From the design view point, this task becomes more complex when the cylinders are fitted with sacrificial anodes or wrapped with layers of marine growth. Despite the successful research conducted for more than five decades to investigate the interaction of fluids with tubular cylinders, much has yet to be discovered to understand the influence of sacrificial anodes and marine growth on drag and inertia coefficients, as the nature and characteristics of the kinematics and dynamics involved are complex and non-linear, as both sacrificial anodes and surface roughness can affect the flow regimes and the fluid structures interaction phenomenon. In offshore structures, designers normally use the well-known Morison equation (Morison,

Johnson et al. 1950) for estimation of total hydrodynamic forces which consists of drag and inertia forces superimposed linearly, using the appropriate drag and inertia coefficients as recommended by the design codes of practices. For instance, API (API 2007), DNV (DNV 2010), and ISO (ISO 2007) provide recommended specific values for hydrodynamic coefficients depending on whether the cylinder is smooth or fouled. In practice, these coefficients are taken as constant parameters, although drag and inertia force coefficients are determined as functions of Reynolds number ( $Re$ ),  $KC$  number, wave and current parameters, member shape, surface roughness, size and orientation of the cylinder.

The concept of estimating hydrodynamic forces on circular cylinders is not new. The review of the existing literature suggests that many researchers have explored the flow over circular cylinders in order to determine drag and inertia forces accurately. The pioneering experimental investigation of drag and inertia coefficient was conducted by Morison, et al. (Morison, Johnson et al. 1950). Later, Sarpkaya (Sarpkaya 1979) conducted experimental investigations to determine drag and inertia coefficients as a function of  $Re$  and  $KC$  number. Similar experimental investigation was also conducted by Chakrabarti (Chakrabarti 1981). Additional materials pertaining to this area of research can be found in (Sarpkaya 1986), (Justesen 1989), (Troesch and Kim 1991), (Bryndum, Jacobsen et al. 1992), (Yuan and Huang 2010). However, there are no reported studies that address the effects of anodes on hydrodynamic coefficients. Further, as the marine growth characteristics vary with geographical regions and with water depth, and the size and shape of sacrificial anodes have specific design requirements, this paper reports on experimental investigations of sacrificial anodes and marine growth on hydrodynamic coefficients of rigid cylinders for offshore applications with more emphasis in Malaysian waters. For recent studies on the topic one can refer to (Al-Yacoubi, Kurian et al. 2014) and (Kurian, Al-Yacoubi et al. 2014).

### BACKGROUND CONSIDERATIONS

#### Sacrificial Anodes

Sacrificial anodes are part of the corrosion protection system, commonly known as cathodic protection (CP) system used in offshore engineering to mitigate corrosion of platforms and vessels. Since anodes are designed specifically to corrode instead of the more expensive platforms, they are normally called sacrificial anodes. CP is

one of the most effective and technically appropriate methods adopted for controlling corrosion of offshore platforms. The sacrificial anode protection employs a corrosive cell. The metal to be protected is electrically connected to another metal which is more reactive in a specific environmental condition (Cicek 2013). This method is widely used in the oil and gas industry for the protection of ships, boats, and jacket platforms. Sacrificial anodes are utilized either alone or in conjunction with protective coatings which is mainly limited to splash zones. However, the existence of such protruded objects on structures can significantly influence the hydrodynamic forces on these structures. Typical details of a sacrificial anode with a total mass of 356 kg and its orientation with respect to wave headings as adopted in this study is presented in Fig.1.

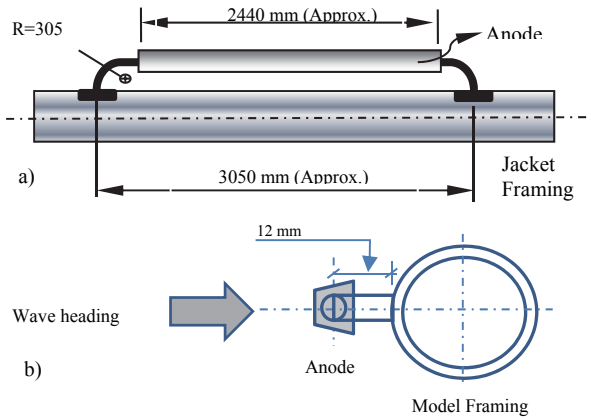


Fig. 1. Definition sketch showing details of sacrificial anode (a) and its orientation with respect to wave headings in the wave tank (b)

## Marine Growth

Marine growth also commonly known as marine fouling is defined as unwanted rough surface coating caused by marine organisms such as plants, animals, micro-organisms, bacteria and algae, on underwater surfaces of marine structures, ships, buoys or offshore platforms, (Norsok 2007). Marine growth accumulation on offshore platforms varies with the geographical region and with water depths. Generally, marine growth near the mean water level is the most critical, however in some areas it can be significant even up to 60 m or more below the mean water level (API 2007). For Malaysian waters, marine growth thickness of up to 127 mm is to be considered in wave force computations, with dry unit weight of marine growth to be taken as  $10 \text{ kN/m}^3$  (PTS 2012). Knowledge on the effects of marine growth on offshore structures is important for accurate estimation of total hydrodynamic forces as marine growth can increase the tubular pipe diameters and consequently, the added mass and the hydrodynamic loading increase. This phenomenon can result in hydrodynamic instability, as a result of vortex shedding and possible corrosion effects (Norsok 2007). Definition sketch showing the surface roughness height and surface roughness thickness is depicted in Fig 2. Hence, better understanding of the effects of these parameters can result in more cost effective design of offshore platforms.

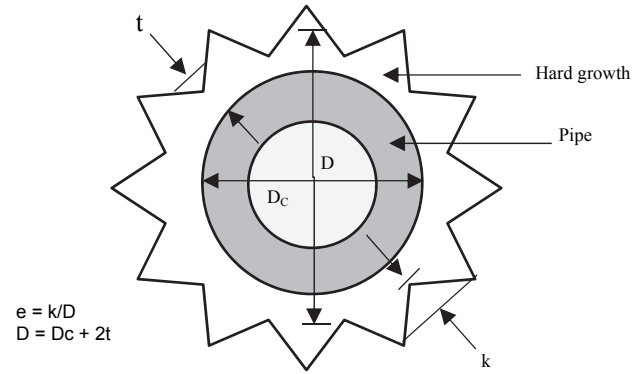


Fig. 2. Definition sketch showing surface roughness height and marine growth roughness thickness (API 2007)

## WAVE TANK MODEL SET-UP

Figs. 3, 4 and 5 show the model set up in the wave tank for smooth, anode fitted and marine growth wrapped cylinders receptively. The model consists of vertical cylinders made of galvanized steel, fixed at the top as cantilever beams. The smooth cylinder and the pipe fitted with sacrificial anodes have a total length  $L = 1.32 \text{ m}$ , with outer diameter  $D_o = 42 \text{ mm}$ , and a wall thickness  $t = 2.5 \text{ mm}$ , giving an aspect ratio of  $L/D_o = 31.4$ . Whilst the cylinder wrapped with surface roughness has an average outer diameter  $D_o = 46 \text{ mm}$ , which gives an aspect ratio of  $L/D_o = 28.7$ . Initially, a smooth cylinder was tested, then, cylinders with sacrificial anodes and marine growth effects were tested and the results were compared. The model fitted with sacrificial anodes consists of six metal pieces fitted in the wetted length of the cylinder as depicted in Fig.4. The length of sacrificial anode is 60 mm, with center to center spacing of 120 mm. For marine growth modeling, sand papers with surface roughness height  $k = 1 \text{ mm}$  were used to cover the cylinder (Fig.5). In this experimental set up, all the cylinders were fitted with wave force sensors designed especially for this research by the research group. The force sensors are capable of measuring the total hydrodynamic forces accurately. The physical properties of the different models and the scaled up prototype details are shown in Table 1.

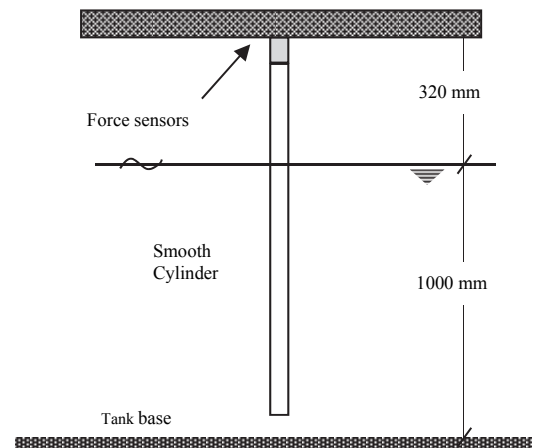


Fig. 2. Details of the smooth cylinder model setup in the wave basin

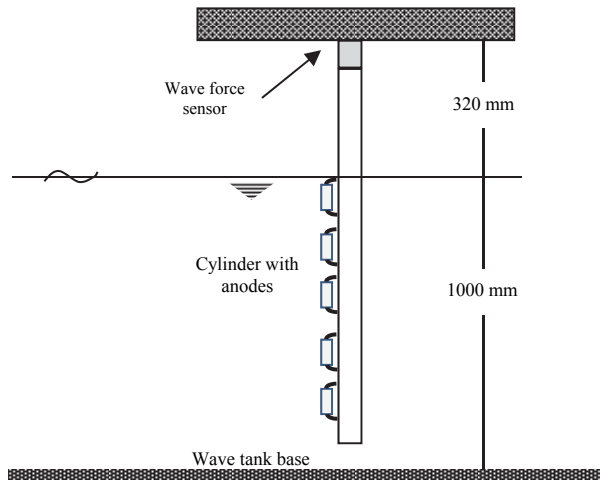


Fig. 3. Detail of the model setup in the wave tank for a tubular cylinder fitted with sacrificial anodes

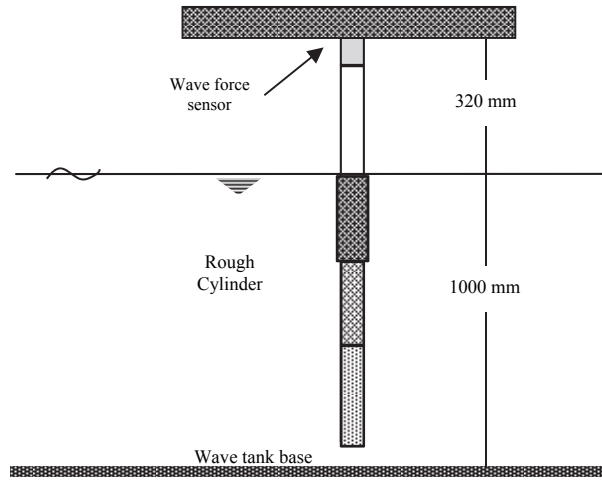


Fig. 4. Details of the model setup in the wave tank for a tubular cylinder wrapped with marine growth

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

Model			Prototype			
Wave Period (s)	Frequency (Hz)	H(m)	Wave Period (s)	Frequency (Hz)	H(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	14.830	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

Table 2. Details of wave parameters used

Type of Cylinder	Model			Prototype		
	Pipe Diameter (m)	Pipe Length (m)	Wall Thickness (mm)	Pipe Diameter (m)	Pipe Length (m)	Wall Thickness (mm)
Smooth & anode fitted cylinders	0.042	1.23	25	2.31	67.65	137.5
Marine growth wrapped cylinder	0.046	1.23	25	2.53	67.65	137.5

## Experimental Program and Wave Condition

The model tests were carried out in the wave basin at Universiti Teknologi PETRONAS (UTP), Malaysia. The wave tank dimensions are 20 m by 10 m, with a maximum water depth of 1 m. In this study, regular waves with wave heights  $H$  ranging from 20 mm to 200 mm, and corresponding to tank wave periods varied from 1s to 3s were generated. The wave-maker was controlled through an integrated remote control software package capable of generating regular, random and multidirectional waves. The wave amplitudes were measured

using four wave probes placed at the vicinity of the model at a center to center spacing of 1.8 m, while the wave forces were recorded using a data logger with a sampling rate set as 100Hz. Details of the wave characteristics generated in the wave tank and the corresponding full scale prototype wave parameters estimated in accordance with Froude scaling law are presented in Table 2. The scaling similitudes were conducted in accordance with Froude scaling law (Chakrabarti 1994).

## THEORETICAL CONSIDERATIONS

In this section, theoretical methods adopted for estimation of hydrodynamic forces and the corresponding force's coefficients are discussed.

### Estimation of Hydrodynamic Forces and Coefficients

To estimate the maximum hydrodynamic forces acting on the cylinder from the time series records, the forces corresponding to each wave cycle were individually analyzed and the results were compared at different  $KC$  number. This cycle was taken as the average of a number of cycles of stabilized force records, and then the measured forces, together with the theoretically estimated forces were utilized to determine drag and inertia coefficients corresponding to each case. As the phase angle  $\theta$  is an important parameter during the estimation of the total hydrodynamic forces and the force's coefficients, the accurate phase angle  $\theta$  that satisfies Equation 1, and corresponds to the optimum  $C_m$  and  $C_d$  values was adopted. In this process, the maximum force  $F_{max}$  of one cycle was considered for each load case as presented in Fig. 6. Then, by substituting the measured forces in the left hand side of Equation 1, and the theoretically estimated forces in the right hand side of the equation, the non-dimensional form of the force can be determined by dividing the measured forces by the theoretically estimated forces. Then, drag and inertia coefficients that satisfy the phase angles ( $\theta_1, \theta_2, \theta_3$  and  $\theta_4$ ) and the non-dimensional forces at crest, trough and zero crossing points of the representative force cycle as presented in Fig.6 were adopted as the optimum hydrodynamic coefficients for each loading case (Kurian, Al-Yacoubi et al. 2014). The total wave forces on the cylinder due to drag and inertia forces can be estimated using Equation 1 (Chakrabarti 1987).

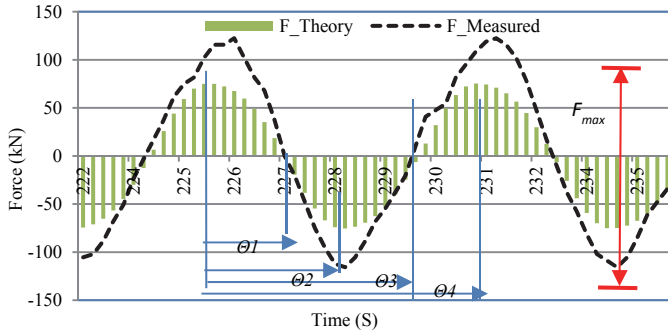


Fig. 5. Schematic diagram showing the measured and theoretically estimated hydrodynamic forces and the phase angles adopted for determination of  $C_m$  and  $C_d$  values (Kurian, Al-Yacoubi et al. 2014)

$$F = \rho g V \left( \frac{H}{2d} \right) \tanh kd \times [C_m \sin \theta + C_d \left( \frac{H}{4\pi D_0} \right) \frac{2kd + \sinh 2kd}{\sinh kd} |\cos \theta| \cos \theta] \quad (1)$$

where  $\rho$  is the water density,  $g$  is the gravitational acceleration,  $V$  is the volume of displaced water  $= \pi D_0^2 d / 4$ ,  $C_m$  and  $C_d$  are the hydrodynamic inertia and drag force coefficients respectively,  $D_0$  is the pipe diameter,  $H$  is the wave height, the phase angle  $\theta = kx - \omega t$ , in which  $k$  is the wave number,  $x = 0$  is the reference position, and  $\omega$  is the wave frequency.

### Keulegan–Carpenter number

$KC$  number is an important parameter to describe the hydrodynamic quantities when a cylinder is subjected to an oscillatory flow, it is mainly relevant for slender cylindrical structures in waves (Sumer and Fredsøe 2010), and can be estimated using Equation 2.

$$KC = \frac{U_m T_w}{D_0} \quad (2)$$

where  $U_m$  is the maximum flow velocity,  $T_w$  represents the wave period, and  $D_0$  is the cylinder diameter. In this study, as the tests were conducted at fixed wave height  $H = 0.1\text{m}$  and at different wave periods varied from 1 to 3 seconds based on the allowable limits of the wave generator. The comparison of the results for the different case studies was presented in terms of  $KC$  number, as 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 ( $d$ ).  $KC$  number was initially introduced by Keulegan and Carpenter (Keulegan and Carpenter 1956) who performed excessive experiments to estimate forces on cylinders and plates subjected to oscillating fluid.

## RESULTS AND DISCUSSIONS

In the following sections, the effects of sacrificial anodes, as well as the effects of marine growth on hydrodynamic forces and the corresponding drag and inertia coefficients are discussed.

### Effects of Sacrificial Anodes on Hydrodynamic Forces

Figs. 7-11 show the comparison of hydrodynamic forces on a smooth cylinder plotted against those of a similar cylinder with the same outer diameter, but fitted with sacrificial anodes. The test was conducted for different  $KC$  number ranging from 9.25 to 14.9. This particular range of  $KC$  number was dictated by the cylinder diameter, the wave kinematics and the wave period generated in the wave tank. The summary of these hydrodynamic forces at different  $KC$  number are depicted in Fig. 12. The test results show that at  $KC = 9.2$  the total hydrodynamic force on the smooth cylinder was 348 kN, while the corresponding force on the cylinder fitted with sacrificial anodes was 364 kN. This indicates that at this particular  $KC$  number, the existence of anodes increased the total hydrodynamic forces by 4.6%. With a further increase in  $KC$  number i.e. from 9.25 to 9.68, the smooth cylinder has experienced a total force of 317 kN. The cylinder fitted with anodes has shown a maximum hydrodynamic force of 406 kN, which means an overall increase of 28% in the measured forces. The graph in Fig. 12 also suggests that the force on the smooth cylinder appears to be continuously decreasing with increasing  $KC$  number before rising again to 156 kN at  $KC = 14.97$ . On the other hand, the cylinder with anodes has experienced the maximum force of 406 kN at  $KC = 9.68$  kN then continuously decreased with increasing  $KC$  number to reach 197 kN at  $KC = 12.93$  before rising again at the end to 211 kN at  $KC = 14.97$  with an overall increase of 34.8% as compared to the smooth cylinder. The above analysis of the results clearly indicates the significant influence of sacrificial anodes on the total hydrodynamic forces of tubular cylinders.

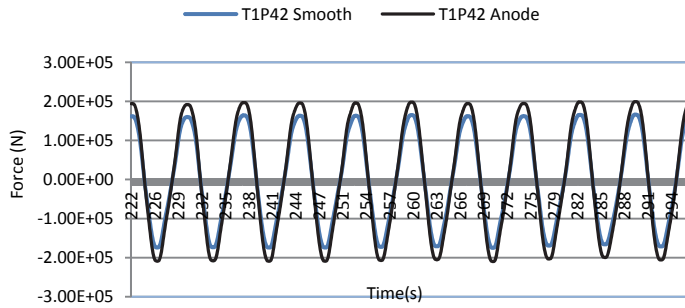


Fig 6 . Comparison of hydrodynamic forces for a 2.31 m smooth cylinder and a similar cylinder with the same outer diameter, fitted with sacrificial anodes, subjected to regular waves with  $H = 5.5\text{m}$  and  $T = 7.416\text{s}$  at  $KC = 9.25$

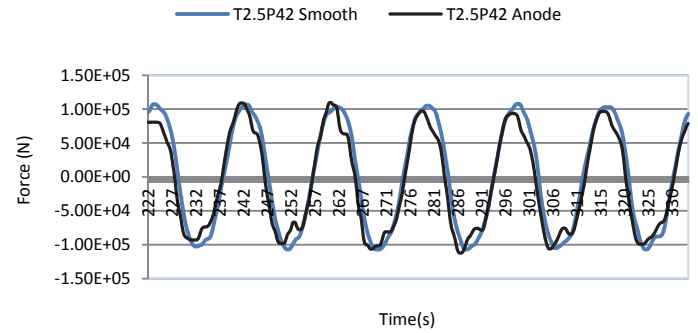


Fig.9. Comparison of hydrodynamic forces for a 2.31 m smooth cylinder and a similar cylinder with the same outer diameter, fitted with sacrificial anodes, subjected to regular waves with  $H = 5.5\text{m}$  and  $T = 18.54\text{s}$  at  $KC = 12.93$

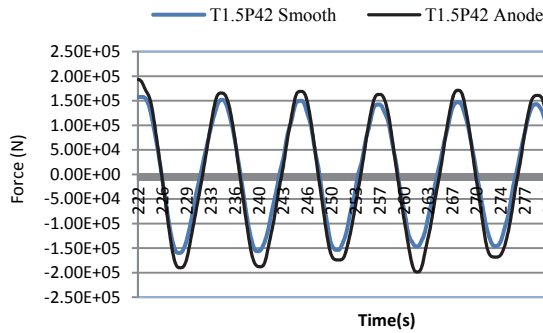


Fig 7. Comparison of hydrodynamic forces for a 2.31 m smooth cylinder and a similar cylinder with the same outer diameter, fitted with sacrificial anodes, subjected to regular waves with  $H = 5.5\text{m}$  and  $T = 11.124\text{s}$  at  $KC = 9.68$

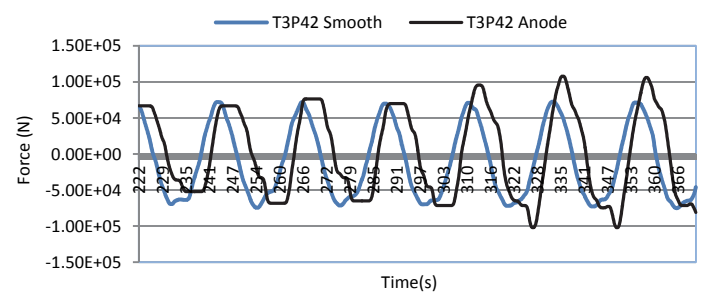


Fig. 10. Comparison of hydrodynamic forces for a 2.31 m smooth cylinder and a similar cylinder with the same outer diameter, fitted with sacrificial anodes, subjected to regular waves with  $H = 5.5\text{m}$  and  $T = 22.249\text{s}$  at  $KC = 14.9$

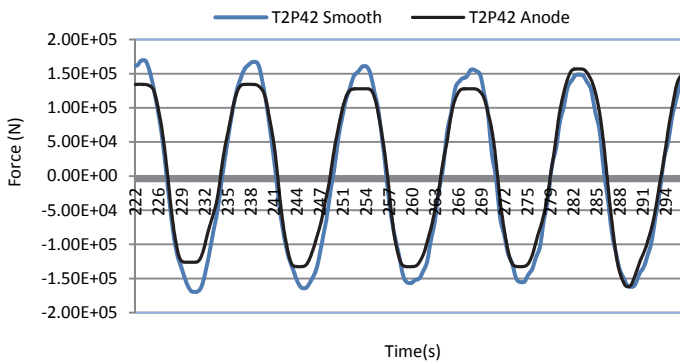


Fig. 8. Comparison of hydrodynamic forces for a 2.31 m smooth cylinder and a similar cylinder with the same outer diameter, fitted with sacrificial anodes, subjected to regular waves with  $H = 5.5\text{m}$  and  $T = 14.83\text{s}$  at  $KC = 11.07$

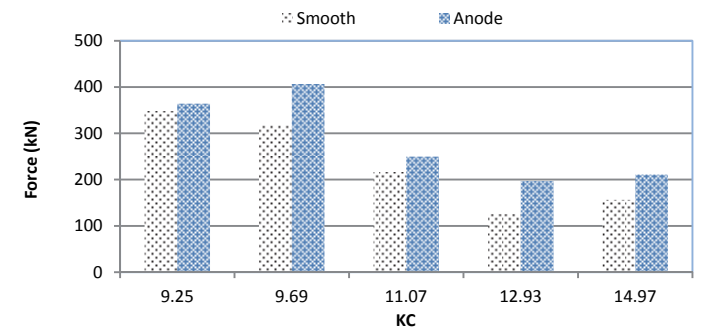


Fig. 11. Comparison of total hydrodynamic forces on a 2.31 m smooth cylinder and a similar cylinder with the same outer diameter, fitted with sacrificial anodes, at different  $KC$  number

### Effects of Sacrificial Anodes on $C_m$ and $C_d$ Values

Fig. 13 shows the variation of drag coefficients with  $KC$  number for a smooth tubular cylinder compared with those of a similar cylinder fitted with sacrificial anodes. The trend of the graph suggests that drag coefficient values vary with respect to  $KC$  number. The maximum value of drag coefficient for the smooth cylinder was observed as  $C_d = 0.51$  at  $KC = 11.07$ , while the minimum drag coefficient  $C_d = 0.34$  was observed at  $KC = 12.93$ . On the other hand, the maximum and minimum drag coefficients for the anodes fitted cylinder were  $C_d = 0.7$  and  $C_d = 0.512$  recorded at  $KC = 9.69$  and  $KC = 12.93$  respectively. Here, one can observe that the minimum values of  $C_d$  for both the

cylinders were observed at  $KC = 12.93$ , nevertheless the maximum  $C_d$  values occurred at different  $KC$  values. Generally, one can observe that in all  $KC$  range, the cylinder fitted with sacrificial anodes has shown greater  $C_d$  values as compared to the smooth one. A maximum increment of 37.3% can be observed for the maximum drag coefficient, while an overall increment of 51 % can be observed on the minimum drag coefficient as a result of sacrificial anodes.

Similarly, the effects of sacrificial anodes on inertia coefficients were investigated experimentally. The trend of inertia coefficients shown in Fig. 14 indicates that  $C_m$  values for the cylinder fitted with anodes are comparatively higher than those of the smooth cylinder, except at  $KC = 11.07$  both the cylinders have almost the same inertia coefficient. Generally, the analysis of the results indicates that the maximum and minimum inertia coefficients for the smooth cylinder are  $C_m = 1.26$  and  $C_m = 0.84$  observed at  $KC = 11.07$  and  $KC = 12.93$  respectively, while for the cylinder fitted with sacrificial anodes, the maximum and minimum inertia coefficients are  $C_m = 1.74$  and  $C_m = 1.26$ , corresponding to  $KC = 9.69$  and  $KC = 12.93$  respectively. From the above comparison one can observe that sacrificial anodes effects on the maximum values of inertia coefficient is 37%, while the minim inertia coefficient was increased by 50%.

The above analysis indicates that the existence of sacrificial anodes can significantly influence the hydrodynamic force coefficients. However, the values of drag and inertia coefficients determined experimentally for both the cylinders are comparatively smaller than the specified values by the design code of practices. According to API (API 2007), the recommended coefficients for a smooth cylinders are  $C_d = 0.65$  and  $C_m = 1.6$ . On the other hand,  $C_m = Cd = 2$  is generally recommended for estimation of forces on circular cylinder with anodes (PTS 2012).

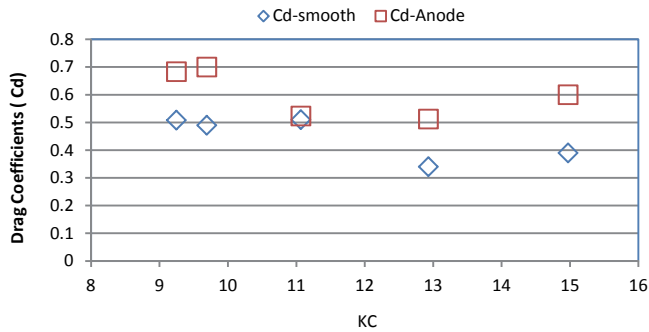


Fig. 12. Comparison showing the variation of drag coefficients with  $KC$  number for a smooth tubular cylinder with outer diameter  $D_o = 2.31\text{m}$  compared with those of a similar cylinder with the same outer diameter, fitted with sacrificial anodes

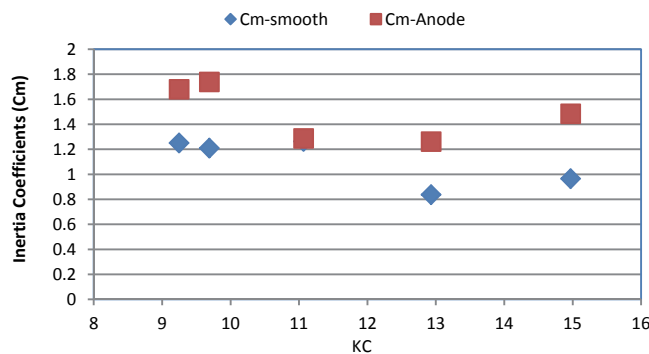


Fig. 13. Comparison showing the variation of inertia coefficients with  $KC$  number for a smooth tubular cylinder with outer diameter  $D_o = 2.31\text{m}$  compared with those of a similar cylinder with the same outer diameter, fitted with sacrificial anodes

## Effects of Marine Growth on Hydrodynamic Forces

Figs. 15-19 show the time series records for the hydrodynamic forces on a smooth and rough cylinder at different  $KC$  number. The summary of the total hydrodynamic forces on both the cylinders at different  $KC$  are depicted in Fig. 20. At  $KC = 9.25$  the maximum hydrodynamic force on the smooth and the rough cylinders are 348 kN and 425 kN respectively. This shows that the marine growth has increased the maximum force by 22%. Further, one can observe that the hydrodynamic forces on the rough cylinder decreased with increasing  $KC$  number to reach the minimum value of 164 kN at  $KC = 14.97$ . Similarly, the forces on the smooth cylinder decreased with increasing  $KC$  number, to record its minimum value of 126 kN at  $KC = 12.93$  before increasing to 156 kN at  $KC = 14.97$ .

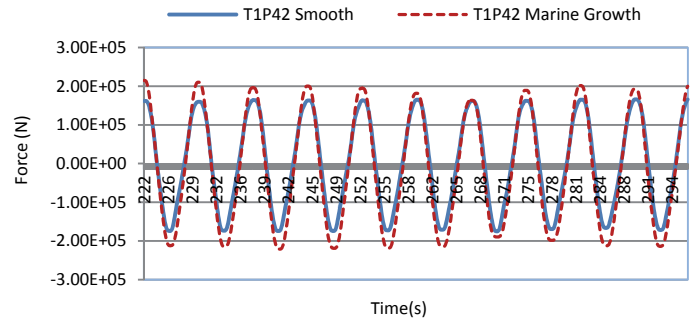


Fig. 14. Comparison of hydrodynamic forces on a 2.31 m smooth cylinder compared against the forces on a similar cylinder with rough surface, subjected to regular waves with  $H = 5.5\text{ m}$  and  $T = 7.416\text{ s}$  at  $KC = 9.25$

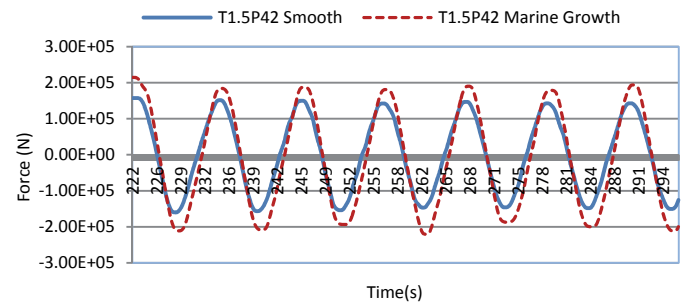


Fig. 15. Comparison of hydrodynamic forces on a 2.31 m smooth cylinder compared against the forces on a similar cylinder with rough surface, subjected to regular waves with  $H = 5.5\text{m}$  and  $T = 11.124\text{ s}$  at  $KC = 9.68$

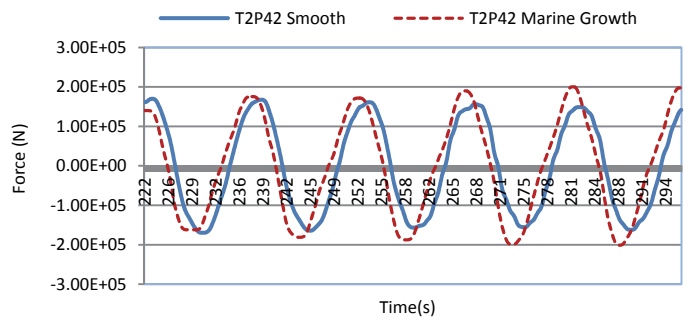


Fig. 16. Comparison of hydrodynamic forces on a 2.31 m smooth cylinder compared against the forces on a similar cylinder with rough surface, subjected to regular waves with  $H = 5.5\text{m}$  and  $T = 14.83\text{ s}$  at  $KC = 11.07$



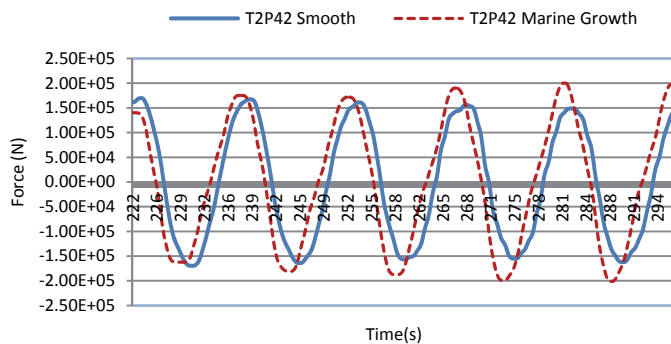


Fig. 17. Comparison of hydrodynamic forces on a 2.31 m smooth cylinder compared against the forces on a similar cylinder with rough surface, subjected to regular waves with  $H = 5.5\text{m}$  and  $T = 18.540\text{s}$  at  $KC = 12.93$

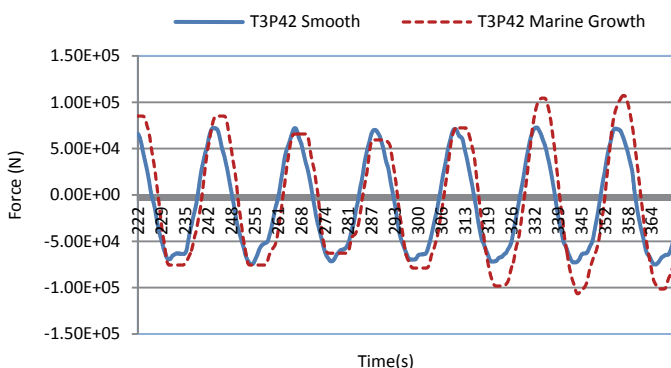


Fig. 18 Comparison of hydrodynamic forces on a 2.31 m smooth cylinder compared against the forces on a similar cylinder with rough surface, subjected to regular waves with  $H = 5.5\text{ m}$  and  $T = 22.249\text{ s}$  at  $KC = 14.97$

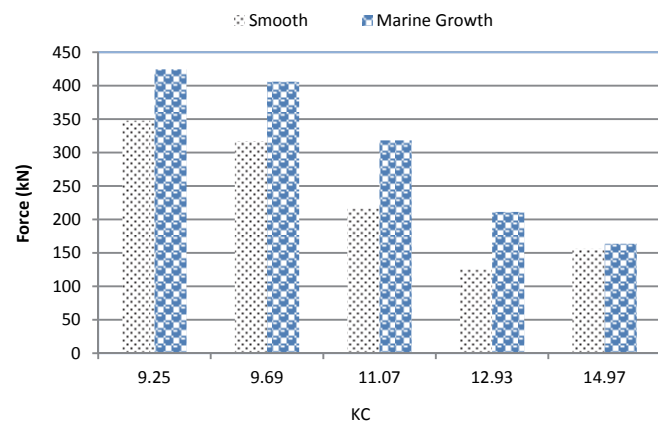


Fig. 19. Summary of forces on a 2.31 m smooth cylinder versus that of a similar cylinder with the same outer diameter, fitted with marine growth at different  $KC$  number

## Effects of Marine Growth on Hydrodynamic Coefficients

Fig. 21 shows comparison of drag coefficients for a smooth and rough cylinder as a function of  $KC$  number. Generally, the cylinder wrapped with marine growth has shown higher drag coefficients as compared to the smooth one. This observation is in good agreement with the forces trend discussed in the previous sections. As drag and inertia coefficient are both functions of the total hydrodynamic forces, higher forces will definitely result in higher hydrodynamic coefficients. Hence, one can observe from the plotted graphs that the maximum and minimum drag coefficients for the smooth cylinder are  $C_d = 0.51$  and  $C_d = 0.34$  estimated at  $KC = 11.07$  and  $KC = 12.93$  respectively, while the cylinder with rough surface has experienced a maximum and minimum drag coefficient of  $C_d = 0.67$  and  $C_d = 0.39$  estimated at  $KC = 9.25$  and  $KC = 14.97$  respectively. Although the highest and the lowest drag coefficients for both the cylinders occurred at different  $KC$  number, one can notice that the maximum  $C_d$  coefficient was increased by 31%, while the minimum drag coefficient was increased by 14.7% as a function of surface roughness. Similarly, Fig. 22 depicts the comparison of inertia coefficients for the same cylinders, under the same loading conditions as discussed in the previous section. The comparison of the results indicates that the variation of inertia coefficients for both the cylinders is consistent with respect to  $KC$  number. For the smooth cylinder, the maximum inertia coefficient was recorded as  $C_m = 1.26$  at  $KC = 11.07$ , whilst the minimum value was estimated as  $C_m = 0.84$  corresponding to  $KC = 12.93$ . On the other hand, the maximum and minimum inertia coefficients for the rough cylinder are  $C_m = 1.65$  and  $C_m = 0.96$  corresponding to  $KC = 9.25$  and  $KC = 14.97$  respectively. This indicates that both the maximum and the minimum  $C_m$  values for the smooth cylinder were increased by 30% and 15% respectively as a result of the surface roughness. Generally, by comparing Fig 21 and Fig 22 with the recommend values of hydrodynamic coefficients for smooth and rough cylinder provided in API (API 2007), one can observe clearly that the estimated  $C_m$  and  $C_d$  values for both the cylinders are slightly smaller than the specified values, except at  $KC = 9.69$  and  $9.25$  the cylinder with surface roughness has experienced inertia coefficients of 1.6 and 1.65 respectively, which are slightly higher than the specified values of  $C_m = 1.2$  recommended by API. Generally, the findings of this study are encouraging as the experimentally estimated values are in fair agreement and comparable to  $C_m$  and  $C_d$  values reported by Chakrabarti (Chakrabarti 1987), thus, the findings might be used for development of mathematical models for prediction of marine growth effects on drag and inertia coefficients more accurately.

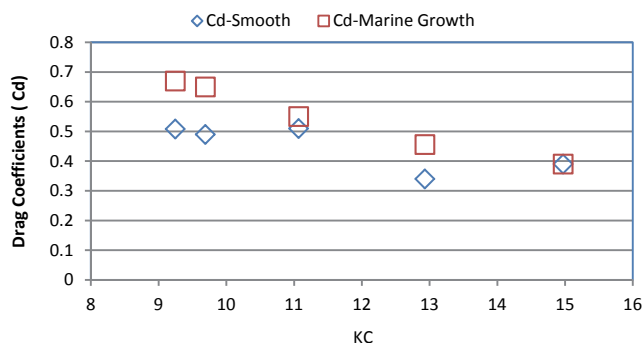


Fig. 20. Comparison of drag coefficients for a 2.31 m smooth cylinder versus a similar cylinder wrapped with marine growth subjected to regular waves with  $H = 5.5\text{m}$  at different  $KC$  number

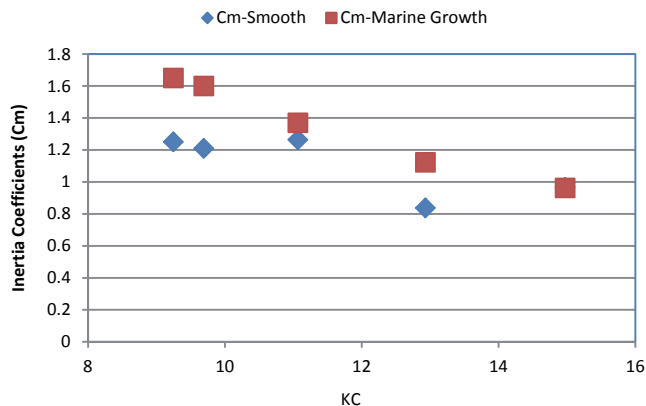


Fig. 21. Comparison of inertia coefficients for a 2.31 m smooth cylinder versus a similar cylinder wrapped with marine growth subjected to regular waves with  $H = 5.5\text{m}$  at different  $KC$  number

## CONCLUDING REMARKS

In this study, experimental investigation was conducted in the wave tank in order to determine and quantify the effects of sacrificial anodes as well as the effects of marine growth on the total hydrodynamic forces and the associated drag and inertia coefficients for tubular rigid cylinders in regular waves. The analysis was presented in terms of  $KC$  number. From this experimental study, the following concluding remarks can be drawn for the full scale prototypes:

1. Generally, the comparison of the hydrodynamic forces, and the force coefficients between a smooth and a similar cylinder with the same outer diameter, fitted with sacrificial anodes revealed that anode fittings can significantly increase the total hydrodynamic forces. Consequently, the maximum and minimum drag coefficients increased by 37.3% and 51% respectively, while the maximum and minimum inertia coefficients increased by 37% and 55% respectively.
2. The effects of marine growth on the total hydrodynamic forces and the corresponding force coefficients were investigated in this study. The findings suggest that the presence of surface roughness has increased the total forces significantly. As a result, drag and inertia force coefficients are influenced. Generally, the effects of marine growth on the total hydrodynamic forces varied with respect to  $KC$  number. Thus, the maximum and minimum drag coefficients increased by 31% and 14.7% respectively, while the maximum and minimum inertia coefficients increased by 30% and 15% respectively, as a result of surface roughness.
3. Generally, the findings of this experimental study are in fair agreement with the results available in the literature as well as the recommended values in the design code of practices. Most of the estimated  $C_m$  and  $C_d$  values are comparatively smaller than the recommended values.

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