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DOI:
10.47964/1120.9172.18485

Available online at www.easdprocedia.org
EASD Procedia EURODYN (2020) 2123-2133

EASD Procedia

EURODYN 2020
XI International Conference on Structural Dynamics
M. Papadrakakis, M. Fragiadakis, C. Papadimitriou (eds.)
Athens, Greece, 23–26 November 2020

TALL OFFSHORE STEEL WIND TURBINE TOWERS UNDER WIND, CURRENT AND WAVE LOADING: AN EXPERIMENTAL AND NUMERICAL STUDY

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Keywords: Wind turbine tower, Offshore Wind Turbines, Monopiles, Dynamic analysis, Current-wave-wind interaction

Abstract. *In the present paper the dynamic response of tall offshore monopile steel wind turbine towers under wind, wave and current during the erection stage is studied. In particular, in the present paper the effect of current-wave-wind interaction as dynamic loading on the dynamic response of offshore wind turbine towers is for first time studied experimentally. A statistical analysis of the dynamic displacements of the model is conducted to study the effect of various loading states on the respective dynamic response. As outcome of the present study it was confirmed that the current field strongly affects the dynamic response of offshore monopoles and in particular, more significantly than the wave field. In the final part, an advanced finite element model is proposed for the efficient study of the structural response of the tower model during erection under current, wave and wind interaction.*

ISSN:2311-9020 © 2020 The Authors. Published by EASD Procedia.
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doi: 10.47964/1120.9172.18485

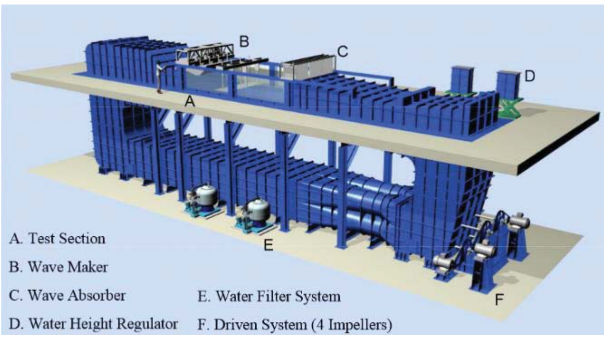
1 INTRODUCTION

In marine environment there are more complicated environmental actions on offshore wind turbine towers (e.g. wind, wave and current loadings) than on the onshore ones. In engineering practice, the wind turbine towers as monopiles need to be constructed during the erection stage in marine environments where current and waves interact. Several researchers have studied the structural characteristics of wind turbine towers during the erection stage by using numerical simulation methods. Tziavos *et al*. [1, 2] studied current practice in terms of engineering methods used for the determination of loads acting on monopile offshore towers and the numerical methods used for the investigation of its structural behaviour. With respect to hydrodynamic loads on monopile wind turbines, the popular linear wave theory along with the Morison equation can be used to model normal sea states, whereas higher-order wave models are necessary to investigate severe events such as wave breaking. Offshore monopile wind turbine towers during the construction stage in marine environment have to resist wind, waves and currents. In this paper the effect of the current action on the dynamic behavior of offshore monopile wind turbine towers is first considered experimentally and then, an appropriate numerical model to study the respective structural dynamic response of the tower is proposed.

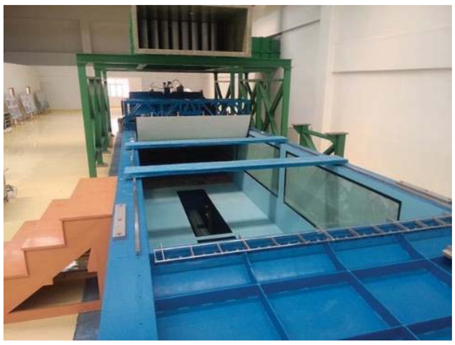
2 EXPERIMENTAL SETUP

2.1 Test facility

The experiment of a monopile subjected to wind, waves and current was performed at the Wind Tunnel and Circulating Water Channel Lab, Shanghai Jiao Tong University in China. The Lab consists of two large-scale facilities, the multifunctional wind tunnel and the circulating water channel with the capability to create an environment of currents, waves and sea wind. In particular, the channel is able to simulate various marine environments including current, waves, sea wind and stratified flow. For the specific experimental setup, wind field and current field at a uniform velocity along the tower height and periodic regular wave was provided.



a. A full image



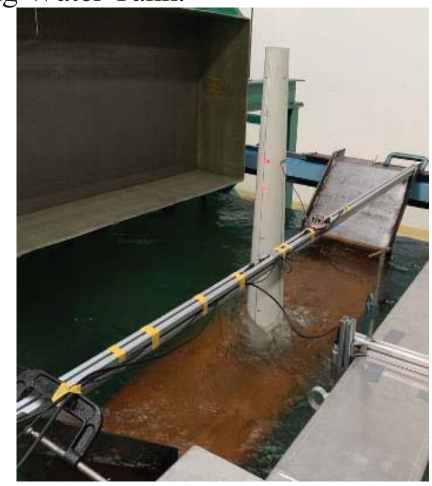
b. Actual test section

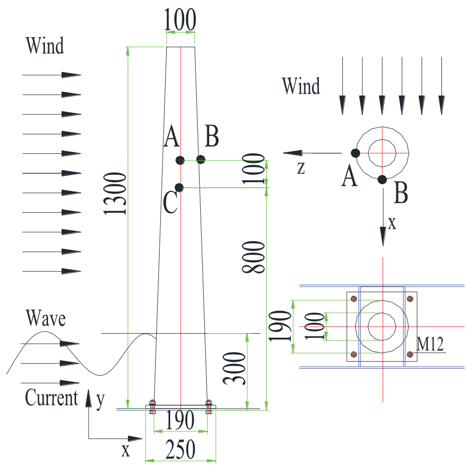
Figure 1. The facilities at the Wind Tunnel and Circulating Water Channel Lab, SJTU.

2.2 Description of the tower model

The prototype monopile structure is a 75m height offshore wind turbine tower during the erection stage. Figure 2 depictes that experimental measurement setup and the dimensions of the tower model. The experimental model is installed in the Wind Tunnel and Circulating Water Tank as shown in Figure 2. The prototype is located at a site with a water depth of 23m, its external radius on the base is 7m and that on the top is 3.75m. The monopile is fixed in the seabed, whilst the model was manufactured with a geometrical scaling of 1:75. The dimensions of the tower model are displayed in Figure 2b. The height of the scaled down tower is 1.3m, 1.0m height above the water surface level and 0.3m height under water depth respectively. The diameter of the tower model varies linearly along its height from 190mm at the bottom to 100mm at the top as shown in Figure 2b. The thickness of the tower model is 0.5mm and the tower is fixed by four Φ12 bolts. As is well-known in an actual wind tunnel or water tank test to balance Froude and Reynolds numbers is a hard task and to this end, the Froude laws of similitude had been used for the physical modelling of the properties of the tower model.

The monopile response was measured by using one accelerometer at 90cm height of point B on the leeside of the tower model in x-axis direction and one sensor head at the 80cm height of the point C in cross section direction in z-axis direction and the other one at the 90cm height of the point A in cross section direction to measure the velocity values in z-axis direction. All the transducers were connected with their corresponding data acquisition instruments. The wave gauge is employed to measure the wave elevation when applying wave loads in the Circulating Water Tank.





a. Actual experiment setup b. Dimensions of the tower model (in mm)

Figure 2. Experimental setup and dimension of tower model

2.3 Loading states

In the experiment various loading cases were considered to study the effect of wind, waves and current loadings on the dynamic response of offshore wind turbine towers. For the wind loading, the wind speed was gradually increased from 5m/s to 28m/s in the wind tunnel. For the current loading, its velocity with a stepwise increase was performed in the range of 0.3m/s to 2m/s. For wave loading, as wave elevation was ranged from 20mm to 50mm for wave periods from 0.5s to 1.25s in the water tank, the corresponding wave heights at the wave periods of 0.5s, 0.75s, 1s and 1.25s being respectively 44mm, 32mm, 25mm and 22mm. The wave shape was the most stable one when wave maker was initially launched, then the new wave was taken to break gradually due to the reflection of the previous wave in the water tank, and therefore, the experimental results should be tested in the beginning of the step of wave generation for the loading states that involve waves.

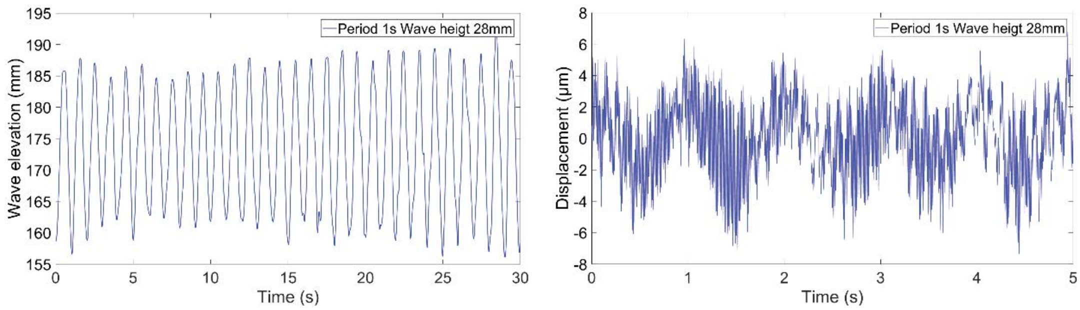
As the lower edge of the air outlet of the wind tunnel is 10cm higher than the still water level in the water tank, current field and wave field could not be affected individually by wind field when wind tunnel is running stably (Figure 2a). For wind-current, wind-wave and wave-current loading states, the three loading states can be performed by combining wind loading and current loading, wind loading and wave loading, wave and current loading. For the wind-current-wave loading states, the wind field should be first flow in the velocity range of 7.5m/s to 20m/s until a stable state, then, current field is adjusted in the speed range of 0.3m/s to 0.8m/s up to its steady stage and finally wave field is provided in the periods of 0.5s, 0.75s and 1.0s.

3 EXPERIMENTAL RESULTS

Aiming to investigate the effect of various marine loadings on the dynamic characteristics of offshore wind turbine towers during construction, during the present experimental test the following loading states had been separated into four groups a) wind-wave; b) wind-current; c) wind-wave-current; d) wave-current.

3.1 Wind, wave and current

For the loading states of wind only, wind-wave, wind-current and wind-wave-current, the wind speed was gradually increased in the range of 5m/s to 28m/s. In each case, the velocity, acceleration and displacement at points A, B and C were respectively measured in the steady wind field. For the current only, its speed is set in a uniform speed at one loading state varying from 0.3m/s to 2m/s. For wave only, the still water level was 30cm. For each loading case, the period of wave maker is first determined at 0.4s, 0.5s, 0.75s, 1s and 1.25s, and then the wave height had been monitored by wave gauge. Figure 3 shows time histories of wave elevations and displacement responses when wave period is 0.75s and wave height is 28mm. According to Figure 3a, for wave height 28mm, the wave period is 1s. According to Figure 3b, it can be observed that as there are two peaks and one valley within each second, the time histories of displacement response exhibit periodicity and the respective periods are equal to the input period of the wave maker.



a. Time histories of wave elevations b. Time histories of displacement responses

Figure 3 Time histories of wave elevations and displacement response of the model under wave only at period of 1s and at wave height of 28mm

The displacement response of the tower model at point C under various loading states is depicted in Figure 4. According to Figure 4, there is regular dynamic response of the tower under wind speeds of 11m/s in the four loading states. Specifically, for the loading states of wind only, the regular dynamic response of the tower at point C exists only at wind speed 11m/s. For the loading of wind-wave and wind-current, the regular dynamic response of the tower under low current speeds and low wave periods respectively are depicted in Figures 4b and 5c, where the dynamic response of the tower becomes irregular gradually as soon as the current speed and the wave period increase. For the loading states of wind-wave-current, the regular dynamic response of the tower under the combination of low current speed and low wave period still occur, they however disappear as soon as current speed and wave period increase. For the loading states of wave only and current only, the dynamic responses of the tower were both irregular in the present experiment.

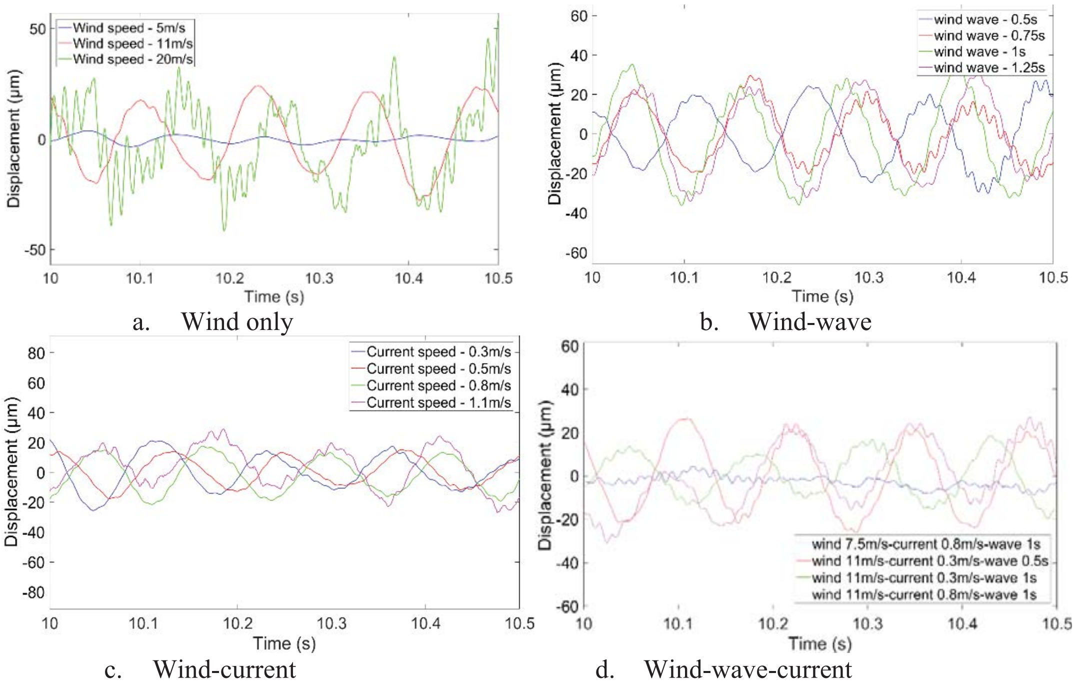
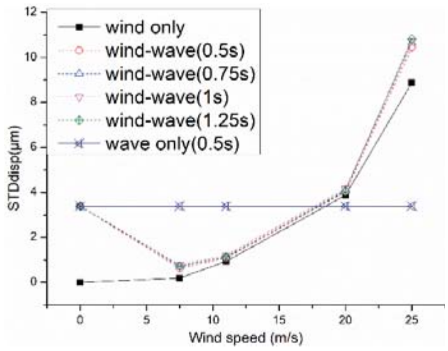
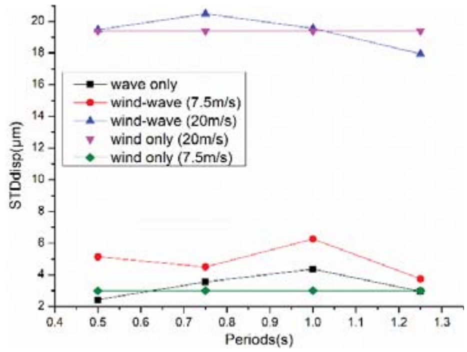


Figure 4 Displacement response of the tower model at point C under various loading states

For the wind-wave loading cases, wind loading was chosen at wind speeds of 7.5m/s, 11m/s, 20m/s and 25m/s and the wave maker produced wave loadings at the periods of 0.5s, 0.75s, 1s and 1.25s with wave heights 44mm, 32mm, 28mm and 22mm respectively. Figure 5 shows the standard deviation of the displacement of the tower model at various wind speeds under wind only, wave only and wind-wave at various periods of 0.5s, 0.75s, 1s and 1.25s. According to Figure 5a, the standard deviation of the displacement of the tower model declines when wind speed increases from 0m/s to 7.5m/s, and the standard deviations of the displacement of the tower model are less than that of tower model under wave only. Then the standard deviation of displacement of tower model rises with wind speed increasing being greater than that of the tower model under wave only. Therefore, it is concluded that wave loading dominates the structural responses of tower model at a low wind speed loading state, whilst wind loading controls the structural responses of tower model at a high wind speed. Figure 5b provides the standard deviation of the displacement of the tower model under various loading states at wind speeds 7.5m/s and 20m/s and at periods 0.5s, 0.75s, 1s and 1.25s. Thus, for the 7.5m/s wind loading case, wave significantly affects the dynamic responses, whilst for the 20m/s wind loading case, wind predominantly controls the dynamic response of the monopile with the wave period varying. For the loading case of wind-current, a similar tendency can be observed where current only affects the dynamic response of the tower at low wind speed, whilst wind controls the dynamic response of the tower in the case that wind speed increases.



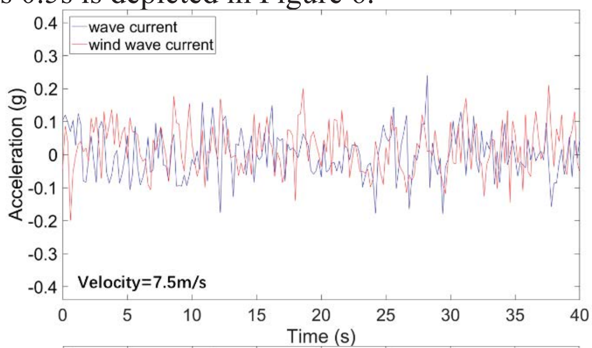
a. STD displacement versus wind speed



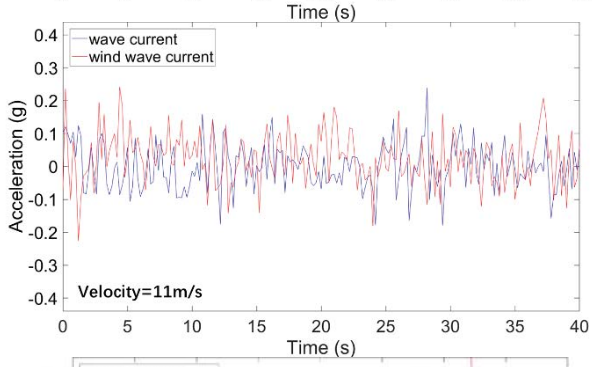
b. STD displacement versus periods

Figure 5 Standard deviation of the model displacements under wind only, wave only and wind-wave

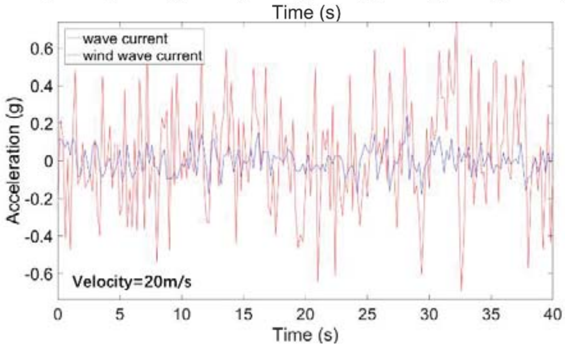
For the wind-wave-current loading state, wind loadings correspond to wind speeds of 7.5m/s, 11m/s and 20m/s, current loadings are set at current velocities of 0.3m/s, 0.5m/s and 0.8m/s, wave loadings are provided at wave periods of 0.5s, 0.75s and 1s. The wind field first runs at a stable state and then, current field is stabilized and at a final stage the wave field is made by using wave maker. Acceleration response of model under wind-wave-current and wave-current loading states at wind speed of 7.5m/s, 11m/s and 20m/s when current speed is 0.3m/s and wave period is 0.5s is depicted in Figure 6.



a.



b.



c.

Figure 6 Accelerations of the tower model under wind-wave-current and wave-current loading states

It was found that the combination of wave and current action only affects the dynamic response of the model in a low and medium wind speed; for a strong wind speed, wind still controls the dynamic responses of the tower.

3.2 Wave and current

With reference to the loading states of wave and current, loading states including wave only, current only and wave-current were considered to study the effect of wave and current on the dynamic response of the model. In this loading case, the current speed was 0.3m/s, 0.5m/s, 0.8m/s and 1.1m/s respectively and wave periods were set at 0.5s, 0.75s, 1s and 1.25s.

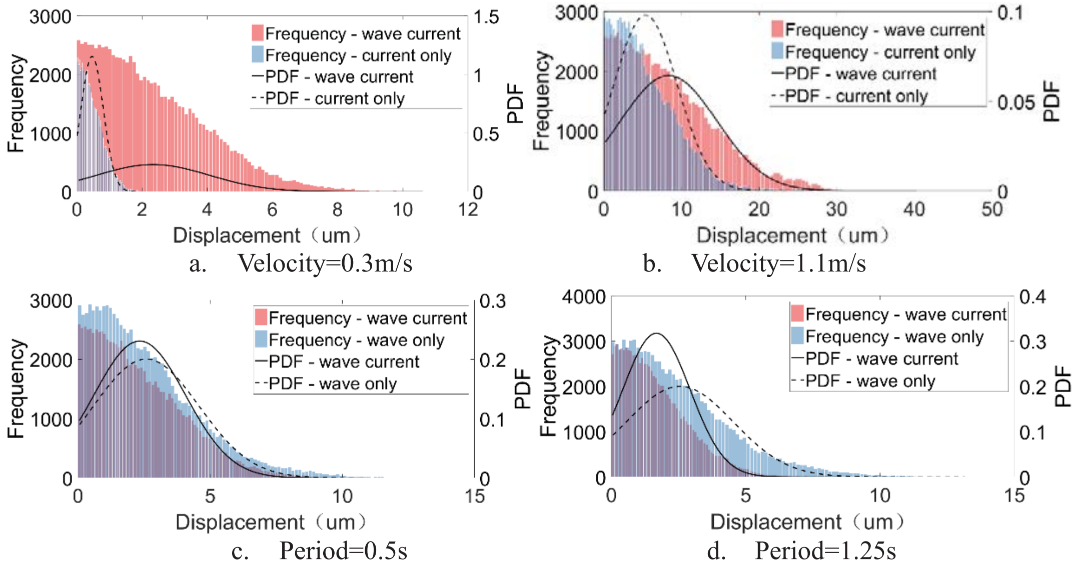


Figure 7 Probability characteristics of the displacements at point C under current speeds of 0.3m/s and 1.1m/s (wave period=0.5s) and wave periods of 0.5s and 1.25s (current speed=0.3m/s)

The probability characteristics of the displacements at point C under current speeds of 0.3m/s and 1.1m/s and wave period of 0.5s and 1.25s appear at Figure 7. The frequency in these figures is the number of any displacement value of the tower under various loading states. For the loading case at current speed of 0.3m/s, the probability function of displacement of the model under wave-current ranges in a wider displacement amplitude than that of the tower model under current only (shown in Figure 7a), which means that the wave dominates the structural response of the tower at this low current speed.

For the loading case at current speed of 1.1m/s, displacement amplitudes under wave-current and current only increase whilst probability functions move closer in the sense that current field principally controls the dynamic response of the monopile at current speed of 1.1m/s. According to Figures 7c and 7d, the value of displacements of the tower under wave only can always surpass that of the tower model under current-wave with the wave period increasing from 0.5s to 1.25s, the two PDFs only move slightly each other which indicate that wave period increase could not affect very significantly the dynamic response of the tower model under wave-current loading state.

4 NUMERICAL SIMULATION

4.1 Loadings

In marine environment the offshore monopile wind turbine towers during the erection stage are subjected to wind, current and wave loadings.

4.1.1 Wind and current loading

Wind loading can be applied to the tower wall as pressure around the tower cross section. The wind flow created at the wind tunnel is a uniform wind field at different wind speeds and the wind pressure on the tower model is related to the wind speed based on the Bernoulli equation as follows:

$$P_w = 0.5\rho_a v_a^2 \quad (1)$$

where P_w is the wind pressure, ρ_a is the air density (1.25kg/m^3) and v_a is the wind speed.

According to EN 1991-1- 4 [3], the external wind pressure corresponds to different profiles with reference to the circular cylinder. Reynolds number are respectively given by the equation:

$$R_e = vD/\nu \quad (2)$$

where R_e is the Reynolds number, v is the fluid speed, D is the diameter of the tower and ν is the kinematic viscosity of fluid.

With reference to the current loading, this is transferred into pressure according to the Bernoulli equation:

$$P_c = 0.5\rho_w v_c^2 \quad (3)$$

where P_c is the current pressure, ρ_w is the water density (1000kg/m^3) and v_c is the current speed.

4.2.2 Wave loading

For the wave loading, this is obtained by the Morrison's equation as the offshore monopile is a slender cylindrical structure fixed in the seabed. According to Morrison's equation [4],

$$dF = \rho_w \frac{\pi D^2}{4} dz C_M a + \frac{\rho_w}{2} C_D D dz |u| u \quad (4)$$

where wave moves along the x-direction as shown in Figure 2, a and u is the acceleration and the velocity of undisturbed wave in x-direction, respectively. C_M and C_D are respectively the mass and the drag coefficient for a smooth tubular section (respectively 2.0 and 1.2 in this experiment). For the situation of finite water depth, u and a can be obtained as the equations (5) and (6) [5]:

$$a = \omega^2 A \frac{\cosh k(y+h)}{\sinh kh} \cos(\omega t - kx) \quad (5)$$

$$u = \omega A \frac{\cosh k(y+h)}{\sinh kh} \sin(\omega t - kx) \quad (6)$$

$$\lambda = \frac{g}{2\pi} T^2 \tanh \frac{2\pi}{\lambda} h \quad (7)$$

where ω=2π/T, $k=2\pi/\lambda$, T is the period of the wave, λ is the wave length, A is the amplitude of the wave, t is the time, x is the wave motion direction, y is the vertical coordinate and its positive direction is upwards from water level to the tower top, h is the water depth in the water tank equal to 1.6m in this experiment and g is the gravitational acceleration.

4.2 Validation of the numerical model

The wind turbine tower model was created by the finite element software ABAQUS using the S4R shell element [6]. The tower was considered as fixed at its bottom and manufactured by Q235 steel. Its density and elastic modulus were respectively 7.85g/cm^3 and 206GPa and the Poisson's rate is 0.3. Wind, current and wave loading profiles of the offshore wind turbine tower are shown in Figure 8. In this model, as wind and current loadings are applied as uniform velocity on the slender cylindrical tower structure for each loading state, according to the equations (1, 3), the wind loading can be simplified in accordance to the inventory data [3, 7] and the current loading can be simplified as shown in Figure 8. In the tests the wind speed was kept in the range of 7.5m/s to 20m/s, therefore, the Reynolds number of wind field varies from 0.5×10^5 to 1.5×10^5 being less than 2.0×10^5. The current speeds were varying from 0.3m/s to 2m/s in the Circulating Water Tank during the test. According to equation (2), the Reynolds numbers of current range from 0.3×10^5 to 2×10^5. Therefore, according to the inventory data [3, 4, 5], the distributions of wind and current load coefficients around the circumference can be divided into four parts. The angles of the wind pressure and current pressure around the circumference of the tower cross section were respectively decided to be 60°, 85°, 130° and 85° in this loading states as shown in Figure 8. The wind pressure had been simplified into uniform pressure along the tower height over the water level as wind field is applied as one constant velocity in a stepwise way whilst the current pressure was considered as uniform pressure along the tower height under the water level. For the wave loading, it had been considered as a periodic compressive loading applied on the half section of the tower wall under the water level as shown in Figure 8.

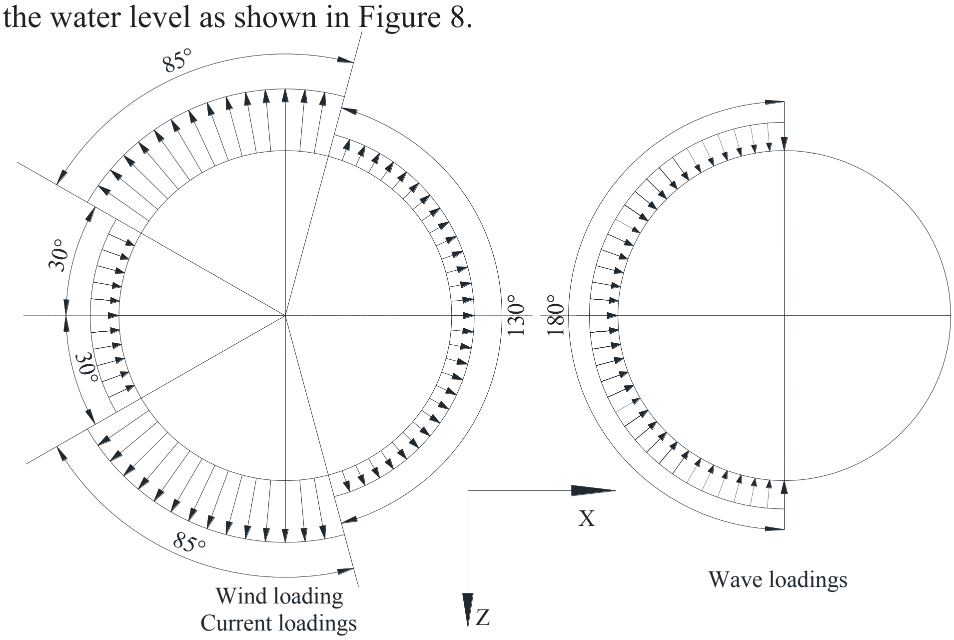


Figure 8 Wind, current and wave loading profile of offshore wind turbine tower

For the loading states of wind speed of 11m/s, current speed of 0.3m/s and wave periods of 0.5s and wave elevation of 44mm, the corresponding wind pressure, current pressure and wave force are calculated by the equations (1)-(7), and therefore, the displacement response at point C of the tower model under wind, current and wave loadings can be obtained from the numerical model. Figure 9 depicts the laboratory test and the numerical results with reference to the displacements at point C of the tower. It is noted that a good agreement between numerical and experimental results had been achieved.

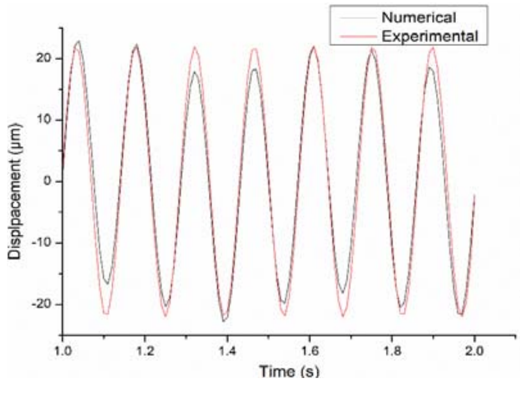


Figure 9 Comparison of time histories of displacement responses of the tower model at point C

5 CONCLUSIONS

In the present paper a Wind Tunnel and Circulating Water Channel was employed to study the dynamic response of offshore wind turbine tower during the erection stage in a marine environment. In this experiment, the loading states of wind-wave, wind-current, wave-current and wind-wave-current were applied to explore their effect on the dynamic response of the offshore tower model. To this end, the later with a geometrical scaling of 1:75 was manufactured and tested under wind, wave and current loadings. Three points A, B and C had been chosen to measure the velocity, displacement and acceleration respectively under the aforementioned selected loading cases. The numerical model of the monopile under wind, wave and current was validated by comparing its results with the experimental ones.

According to the laboratory test results, for the wave loading at low periods and current loading at low speeds, the dynamic response of the monopile under wind-wave, wind-current still occurs regularly, and the dynamic response of the tower is only slightly affected by the wave loading at high periods and current loading at high speeds under the wind speed of 11m/s. For the wind-wave-current loading case, the effect of combination of wave and current on the dynamic response of the tower is significant as displacements of the tower happen irregularly with the wave period and current speed increase. The loading states of wind-wave, wind-current, wind-wave-current and wind only control the dynamic response of the tower as soon as the wind speed increases. For the loading states of wave-current, the effect of the current loading is more significant than that of wave loading on the dynamic response of the tower. Therefore, current loading should not be ignored when the dynamic response of offshore towers in the marine environment is investigated.

6 ACKNOWLEDGEMENTS

The financial support of the present research activity by the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie Grant Agreement No 793316 is gratefully acknowledged. The first author acknowledges with thanks the support of his research provided by the National Natural Science Foundation of China (No. 51808335); the third author acknowledges with thanks the IGI Global Challenges funding Scheme of the University of Birmingham (Project Nr 3035). All authors would like also to thank Mr. Fei Wang, member of the technical staff at Wind Tunnel and Circulating Water Channel at Shanghai Jiao Tong University for his patient work in the laboratory tests.

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