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Dynamic analysis of offshore steel wind turbine towers subjected to wind, wave and current loading during construction

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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. Various loading states involving wind-wave, wind-current, wave-current, wind-wave-current to measure the displacement, velocity and acceleration of the tower model at three points on the tower wall respectively. 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.

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

1. Introduction

Offshore wind energy has developed rapidly as a clean and renewable energy in recent years, in order to meet increasing demand for power. Gradually, as some countries do not have enough space on land for the development of onshore wind power, and as the technology of offshore wind energy generation also matures, offshore wind farms are beginning to flourish. Whereas in the marine environment, there are more complicated environmental loadings such as wind, wave and current loadings than that on land. Therefore, a more developed offshore wind turbine technology is required so that the offshore installations can resist high and strong combination loads and adapt to marine environment. In engineering practice, the isolated wind turbine tower need be installed during construction stage in marine environments. Therefore, an isolated wind turbine tower subjected to wind, current and wave loadings is studied in this paper.

Wind turbine tower during the erection stage has to resist complicated loadings. Many researchers have paid attention to its mechanical characteristics of wind turbine tower in marine environments. Liu et al. (2017) performed load analysis of offshore Horizontal Axis Wind Turbines involving transient aerodynamic loads, wave loads and structural dynamics, they concluded that aerodynamic damping could significantly affect the structural response and the fatigue load of the tower. Li et al. (2018) studied that a short-term fatigue damage of at the tower base of 15MW FOWT with a spar-type platform under stochastic wind-wave cyclic loads. They employed the rain flow counting method and Miner's rule to calculate the cumulative fatigue damage. It can be found that the combination effect of wind and wave should be considered to explore the fatigue damage in the sea environment for the spar-type offshore floating wind turbine. Jung et al. (2015) compared various foundation modellings of offshore wind turbine tower with monopile and explored their effects on the structural response of a

5-MW offshore wind turbine tower. They found that the flexibility of the monopile foundation should be considered for model analysis as natural frequencies of fixed foundation model could be overestimated by 15% of its actual value. Feliciano et al. (2018) proposed a generalized analytical displacement model to estimate the angular deflection and displacement of the NREL 5MW reference wind turbine tower under aerodynamic loading. They also compared the analytical model with numerical results. Tziavos *et al*. (2018) 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. Then, some researcher also experimentally monitored some scaled down towers or full-scale towers. Kim et al. (2017) conducted a structural health monitoring of dynamic characteristics of a wind turbine tower model with damage and without damage at various points, they applied vibration-based damage detection techniques to verify the numerical model of a 3MW wind turbine tower. Fontecha et al. (2017) launched a wind tunnel experiment for a wind turbine tower model with a geometric scaling of 1:150 to predict its dynamic behavior. Zendehbad et al. (2017) measured vibration behaviors of a full-scale 2MW wind turbine tower by using an optical-mechanical platform. It can be obtained that tower deflections during normal operation are sensitive to the yaw misalignment of the rotor.

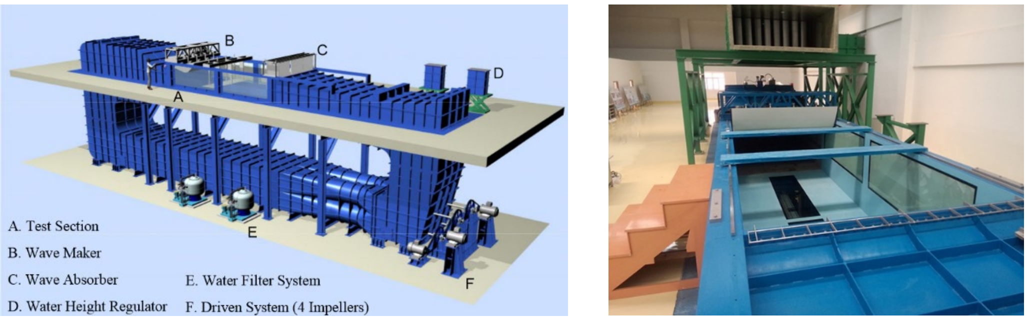
For above mentioned experiments, they are only traditional monitoring for mechanical characteristics of wind turbine tower systems. However, for offshore wind turbine towers during the erection stage, they have to resist winds, waves and currents in marine environments. Therefore, to exploit the effect of environmental loading on the mechanical behaviors of offshore wind turbine towers, a plenty of research have been completed. Karimirad and Moan, 2012 presented the coupled wave and wind-induced motions of spar-type 5-MW wind turbines in harsh and operational environmental conditions. It was concluded that the standard deviations of the responses were primarily wave induced and the standard deviation of the nacelle surge motion under operational conditions was primarily wind induced. Amirinia and Jung, 2017 studied the buffeting response analysis of offshore wind turbines subjected to hurricanes by considering the wind-wave-soil-structure interaction. Sun, 2018 reported the mitigation of monopile offshore wind turbines subjected to wind and wave loading by considering soil effects and damage. It was found that SE and damage presence in the foundation and the tower can change the dominant frequency. Ye and Ji, 2019 carried out the effects of both hydrodynamic and aerodynamic excitations along with the dynamic interaction between the drive-train system and tower structure on the dynamic behavior of the spar-type floating platform under different sea conditions. Banerjee et al. (2019) reported the dynamic response of a 5MW offshore wind turbine with monopile foundation subjected to wind and wave actions by using a multi-degree of freedom system. In their model, they considered the whole wind energy converter as a model with a rotor blade system, a nacelle and a flexible tower and soil-structure interaction effect under stochastic wind and wave loadings. It can be found that soil-structure interaction effect greatly alters the response of the offshore wind turbine structure with blade in the parked condition and in operational conditions. Wei et al. (2016) investigated the static pushover analysis of OWT jackets subject to combined wind and wave loads, they also considered the extreme load directionality, structural orientation, structural geometry and site specification as influence factors to study their effect on the ultimate capacity. Philippe et al. (2013) performed a coupled dynamic analysis of a floating wind turbine system to explore effect of wave direction relative to wind on the wind turbine system. They thought that natural modes of the tower system are excited differently regarding wave direction. Chen and Basu, 2018 estimated fatigue load of a spar-type floating offshore wind turbine by considering effects of current and wave-current interactions. Their results show that the current and the wave-current interaction could have significant influences on FOWT tower and cable responses. Sun and Jahangiri, 2019 employed a three-dimensional pendulum tuned mass damper to reduce the bi-directional vibrations of offshore wind turbine system under wind-wave misalignment to mitigate its fatigue damage. They found that the 3d-PTMD can increase the wind turbine tower fatigue life by more than 50% by studying a NREL monopile 5MW baseline wind turbine with 3d-PTMD. Wang et al (2018) numerically utilized the structural responses of offshore wind turbine with monopile by considering the pile-soil interaction under wind, wave and seismic loadings. They thought that combination of wind, wave and earthquake actions should be involved in the design of wind turbine tower. Marino et al. (2011) proposed a nonlinearly wave model to study a 5MW offshore wind turbine baseline by considering brake wave impact loads. Many researchers have also conducted a lot of work in the field of offshore wind turbine tower under wind and wave loadings. Ren et al. (2019) experimentally investigated the dynamic responses of a new combined TLP type floating wind turbine and a wave energy converter under wind and wave loadings. They also proposed a numerical modelling of the floating wind turbine system to validate their experimental results. However, most current research mainly involved effect of wind and wave loadings on the structural responses of offshore wind turbine towers, they ignored the effect of current loadings in experimental work.

In this paper, the dynamic responses of a scaled-down tower model during the construction phase in marine environments is carried out in the wind tunnel and circulating water channel at Shanghai Jiao Tong University in China. The offshore wind turbine tower with monopile foundation is manufactured with geometrical scaling of 1:75. Dynamic responses of the tower model under wind-wave, wind-current, wave-current, wind-wave-current are respectively measured. Their statistical results of displacement responses of the tower model under various loading states are compared to explore the effect of various loading states on the dynamic responses of the tower model. This paper also proposes a numerical model to study the structural responses of the tower model in marine environment.

2. Experimental setup

2.1 Test facility

The experiment of an isolated wind turbine tower under wind and waves and currents is performed at wind tunnel and circulating water channel, Shanghai Jiao Tong University in China. It consists of two large-scale facilities, the multifunctional wind tunnel, and the circulating water channel with the capability to create the environment of currents, waves, sea wind. The channel can simulate various marine environments including current, waves, sea wind and stratified flow. Its test section dimension is 8.0m long and 3.0m wide and 1.6m deep, and it can provide maximum current velocity 3.0m/s, waves height 0.1m, sea wind velocity 30m/s. A surface flow acceleration system is employed to compensate the boundary layer deficit near the water surface, which improves the flow uniformity. Other supplementary devices, such as water filter system and water height regulator system, are also equipped. The dimension of circulating water channel test section is 2.6m wide and 1.0m high, running separately to simulate sea wind above the circulating water channel, periodical velocity-varying wind field available besides constant wind field. For this experimental setup, it can only provide wind field and current field at one uniform velocity along the tower height and periodic regular wave. As the effect of gradient boundary layer wind in marine environments is less than that on land, it is available to use the uniform wind field. The error due to the limitation of uniform wind field had been ignored in the present experiment.



a. A full image b. Actual test section

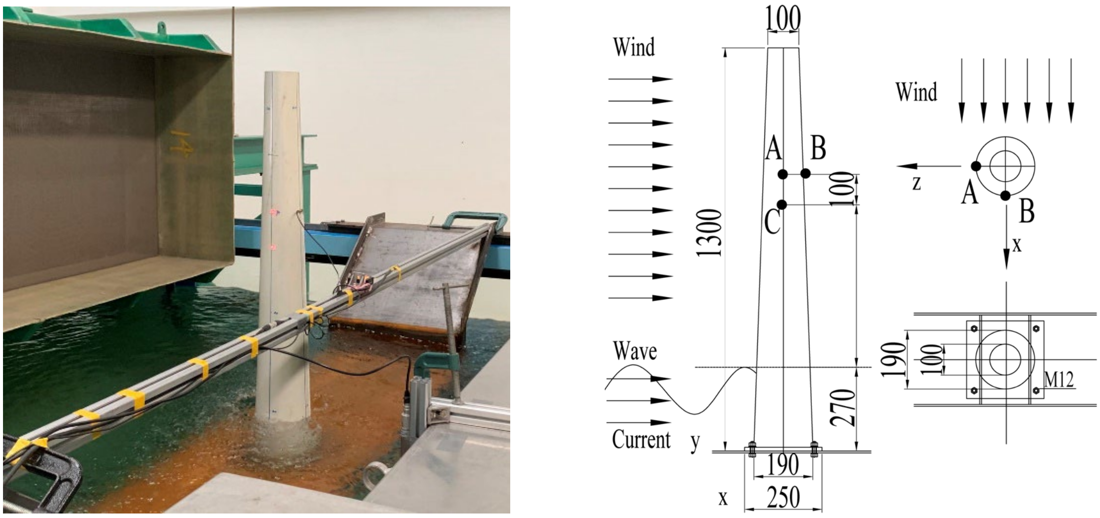
Figure 1 Wind tunnel and circulating water channel

2.2 Description of tower model

The prototype tower structure is an 75m height offshore wind turbine tower with monopile during the erection stage. Figure 2 describes that experimental measurement setup and dimension of tower model. The experimental model is installed on the wind tunnel and circulating water tank as shown in Figure 2. The prototype tower 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 of the tower is fixed in the seabed. The tower model is manufactured with a geometrical scaling of 1:75. The dimension of the tower model can be displayed in Figure 2b. The height of scaled down tower is 1.3m, 1.0m height above the water surface level and 0.27m height under water depth respectively. The diameter of tower model varies linearly from 190mm at the bottom to 100mm on the top along the height as shown in Figure 2b. The thickness of the tower model is 0.5mm and the tower is fixed by four Φ12 bolts.

The natural frequencies of the scaled model and the full-scale tower is 106Hz and 1Hz respectively. The aim of this paper is to present the effect of wind-current-wave interaction on the dynamic response of the scaled tower at the water depth of 27cm. In this test, there are two factors affecting the dynamic response of the tower structure: The first factor is the interaction between the external flow field and the geometrical shape of the structure. The second factor is the natural frequency of the structure. As the geometrical shape of a scaled down structure hardly varies, the effect of the first factor on the dynamic response of the full-scale tower is similar to that of the scaled tower in this experiment, whilst the natural frequency of the full-scale tower can be varied after the tower is scaled down. In the experiment, as the response of scaled tower under different input wind, current and wave fields varies from 0Hz to 100Hz being less than the natural frequency of the scaled tower and taking into account that the aim of this test is to qualitatively explore the level of the effect of the wind, current and wave fields on the dynamic response of the wind turbine tower, the effect of the second factor does not affect the conclusions of the present study.

In the present approach the Reynolds number of the experimental model and the prototype model are respectively in the 0.5×10^5 to 2×10^5 and 10^7 to 10^8 ranges. It can be observed that the Reynolds number in this experiment could not be close to that in engineering practice. As it is not easy to balance the Froude laws and Reynolds laws of similitude., it was decided the Froude laws of similitude to be used for the physical modelling of the properties of the tower model ignoring in the mean time the effect of the Reynolds number. In this experiment, the corresponding Reynolds number should be kept to be greater than the critical Reynolds number that is considered as a common practice in wind tunnel tests and the Froude law was followed in this experiment.

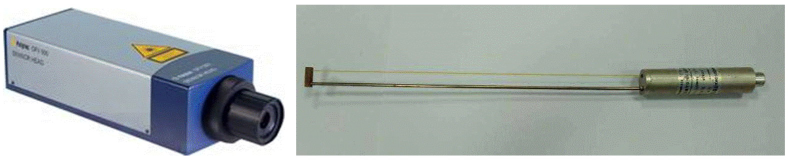


a. Actual experiment setup b. Dimension of wind turbine tower (in mm)

Figure 2 Experimental setup and dimension of tower model

2.3 Measurement instrument

Figure 3 shows that the measurement instruments of this experiment of offshore wind turbine tower. The measurement instruments include one B&W J13232 accelerometer at 90cm height of point B on the leeside of the tower model to monitor the acceleration responses in x-axis direction connected with charge amplifier as shown in Figure 3c, one polytec OFV-505 sensor head as shown in Figure 3a is set at the 80cm height of the point C in cross section direction to monitor the displacement responses in z-axis direction and the other one is lasered at the 90cm height of the point A in cross section direction to measure the velocity responses in z-axis direction. All the transducers are connected with their corresponding data acquisition instruments as shown in Figure 3e. The YWH201-DXX wave gauge as shown in Figure 3b is employed to measure the wave elevation when applying wave loads in the circulating water tank. The sampling rate and resolution of the wave gauge are respectively 100Hz and 1mm. The sampling rate of the data acquisition instrument including displacement meter, speedometer and accelerometer is 4000Hz. Sensitivity coefficients of the accelerate sensor and laser speedometer are respectively 50mv/g and 200mv/mm/s. The velocity resolution and displacement resolution of the polytec OFV-505 sensor are respectively 0.02μm/s and 0.15nm. No filters had been used for the wave gauge and the data acquisition instrument.



a. Polytec OFV-505 sensor head b. Wave gauge

c. Charge amplifier d. Polytec OFV-5000 vibrometer controllers e. Data acquisition instrument

Figure 3 Measurement instrument of the experiment

2.4 Loading states

In this experiment, various loading cases are performed to study the effect of wind, wave and current loadings on the dynamic responses of offshore wind turbine towers. They are respectively wind only, current only, wave only, wind-wave, wind-current, wave-current, wind-wave-current as shown in Figure 2b. For wind only, the wind speed can be increased gradually from 5m/s to 28m/s in the wind tunnel. For current only, its velocity can be risen increasingly in the range of 0.3m/s to 2m/s. For wave only, as wave elevation can be 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 are respectively 44mm, 32mm, 25mm and 22mm. The wave shape is the most stable when wave maker is launched initially, then new wave will be broken gradually due to reflection of previous wave in the water tank, therefore, the experimental results should be tested in the beginning step of wave generation for the loading states involving wave.

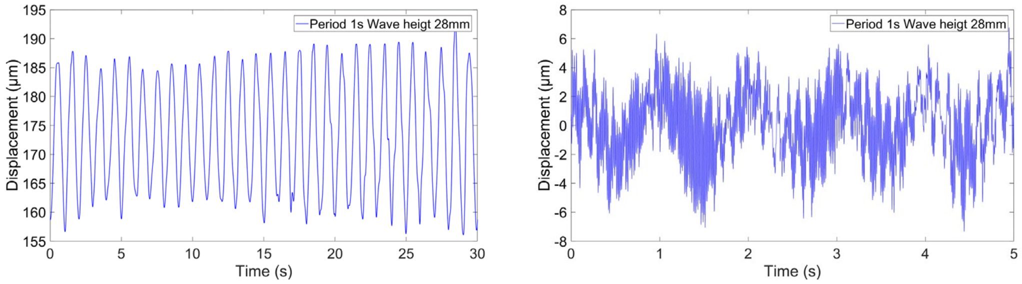
For wind-current and wind-wave loading states, as the lower edge of air outlet of wind tunnel is 10cm higher than the still water level in the water tank, current field and wave field could not be affected individually by wind field when wind tunnel is running stably as shown in Figure 2a. The wind tunnel is firstly run until steady state in the velocity range of 7.5m/s to 25m/s, then current field and wave field is launched step by step in the combination cases respectively in the speed range of 0.3m/s to 1.1m/s and in the period range of 0.5s to 1.25s. For wave-current loading state, the current field is firstly run until its steady in the velocity range of 0.3m/s to 1.1m/s then wave maker starts to provide wave loadings. The wave height can vary in the range of from 22mm to 44mm. Therefore, for wave-current and wind-wave loading states, it only needs to control the period in the range of 0.5s to 1.25s. For wind-current-wave loading states, wind field should be firstly operated 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

In this experiment, to explore the effect of various marine loadings on the dynamic characteristics of offshore wind turbine towers, these loading states should be separated into four groups a) wind-wave; b) wind-current; c) wind-wave-current; d) wave-current. To clarify the experimental result, the statistical analysis of each loading case should be studied.

3.1 Wind, wave and current

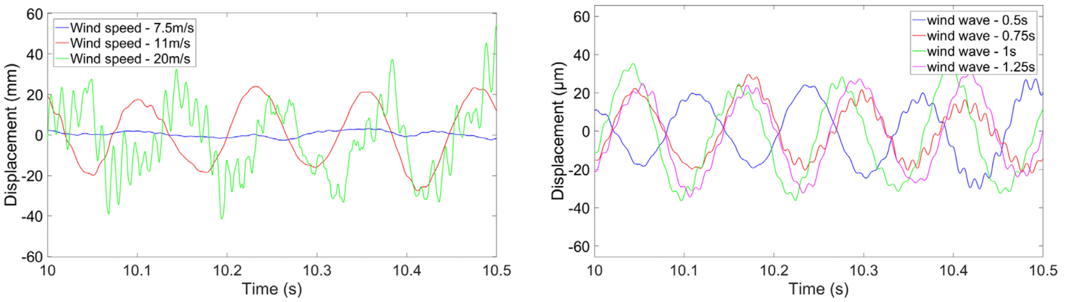
For the loading states of wind only, wind-wave, wind-current and wind-wave-current, the wind speed can be gradually in the range of 5m/s to 28m/s. In each case, the velocity, acceleration and displacement at points A, B and C can be respectively measured in the steady wind field. For the current only, its speed is set in a uniform speed at one loading states varying from 0.3m/s to 2m/s. For wave only, the still water level is 30cm. For each loading case, the period of wave maker is firstly determined at 0.4s, 0.5s, 0.75s, 1s and 1.25s then the wave height can be monitored by wave gauge as shown in Figure 3. Figure 4 shows time histories of wave elevations and displacement responses when wave period is 0.75s and wave height is 28mm. According to Figure 4a, it can be obtained wave height is 28mm in the case that wave period is 1s. According to Figure 4b, it can be observed that as there is two peaks and one valley within each one second, the time histories of displacement responses exhibit to be periodicity, the period is equal to input period of wave maker.



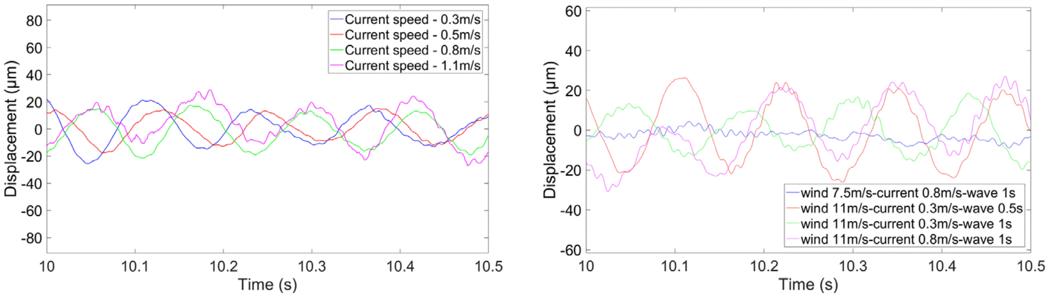
a. Time histories of wave elevations b. Time histories of displacement responses

Figure 4 Time histories of wave elevations and displacement responses of the tower model under wave only at period of 1s and at wave height of 28mm

The displacement responses of tower model at point C under various loading states can be described in Figure 5. According to Figure 5, there are regular dynamic responses 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 responses of the tower at point C only exist at the wind speed of 11m/s. For the loading stats of wind-wave and wind-current, the regular dynamic responses of the tower under low current speeds and low wave periods respectively can still be seen in Figure 5b and 5c, the dynamic responses of the tower become irregular gradually with current speeds and wave periods increase. For the loading states of wind-wave-current, the regular dynamic responses of the tower under the combination of low current speed and low wave periods still occur but they disappear with current speed and wave period increase. For the loading states of wave only and current only, the dynamic responses of the tower are irregular in this experiment.



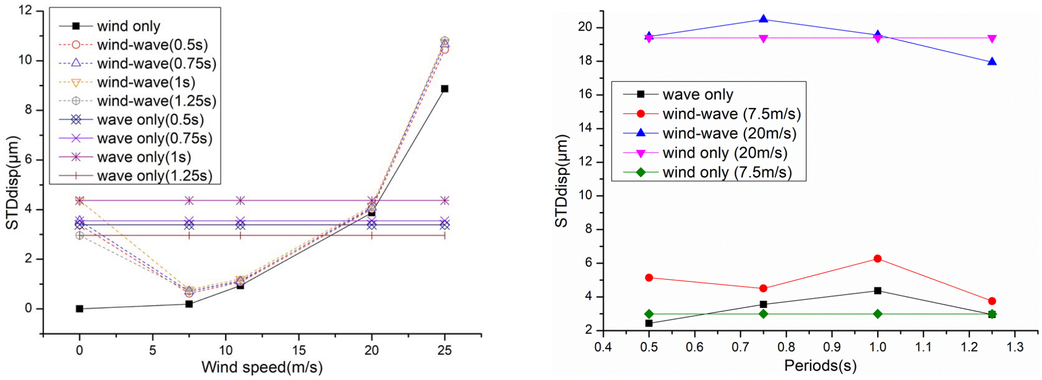
a. Wind only b. Wind-wave



c. Wind-current d. Wind-wave-current

Figure 5 Displacement responses of tower model at point C under various loading states

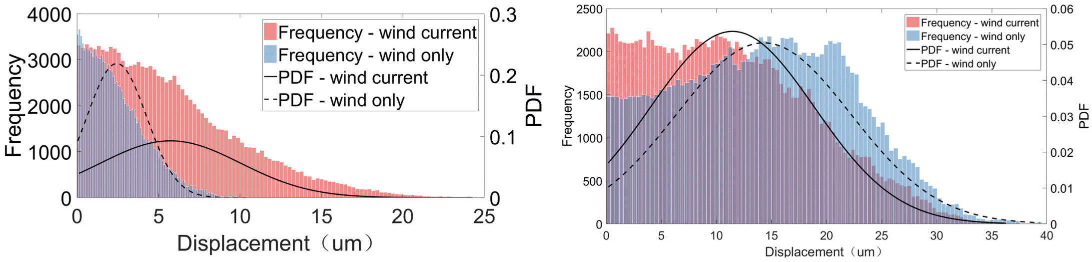
For wind-wave loading cases, wind loadings are chosen at wind speeds of 7.5m/s, 11m/s, 20m/s and 25m/s and the wave maker can produce wave loadings at the periods of 0.5s, 0.75s, 1s and 1.25s with corresponding wave height of 44mm, 32mm, 28mm and 22mm. Figure 6 describes that standard deviation of displacement response of tower model at various wind speeds under wind only, wave only and wind-wave, wave at various periods of 0.5s, 0.75s, 1s and 1.25s. According to Figure 6a, the standard deviation of displacement of tower model declines when wind speed increases from 0m/s to 11m/s, and the standard deviations of displacement of 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 increases and greater than that of tower model under wave only. Therefore, it can be inferred that wave loadings should dominate the structural responses of tower model at a low wind speed loading state whereas wind loadings control the structural responses of tower model at a high wind speed for the wind turbine tower model. According to Figure 6a, the STD of displacement of the tower model under combination of wind only, wave only and wind-wave respectively can be compared. It can be found that the displacement response of the tower model under the combination of wind only, wave only and under wind-wave are different for the scaled tower model at the water depth of 0.27m, whereas the curves of the displacement response of the tower model under wind-wave and under wind only are close each other in accordance to Figure 6a, which demonstrates that the response of the tower model under wind-wave and under wind only are similar. According to aforementioned above, there are two factors affecting the dynamic response of the tower structure in this test. According to Figure 6a, as the displacement responses of the tower model under input wave only and input wind-wave are different dynamic loadings, the input wave only and input wind-wave as the first factor are different. Whereas as for the second factor, the natural frequencies of the tower model under different flow fields are all similar. Therefore, the displacement response of the tower model under the combination of input wind only and wave only respectively are different from those under input wind-wave. Therefore, it can be concluded that the effect of the wave field on the dynamic response of the tower model under wind-wave is very slight at this water depth of 0.27m for the scaled tower model, but the effect of the wind filed could control the dynamic response of the tower model. According to Figure 6b, it provides standard deviation of displacement of tower model under various loading states at the wind speeds of 7.5m/s and 20m/s and at periods of 0.5s, 0.75s, 1s and 1.25s. Thus, for the 7.5m/s wind loading case, wave can affect significantly the dynamic responses. Whereas for the 20m/s wind loading case, wind could predominantly control the dynamic responses of tower model with the wave period varies.



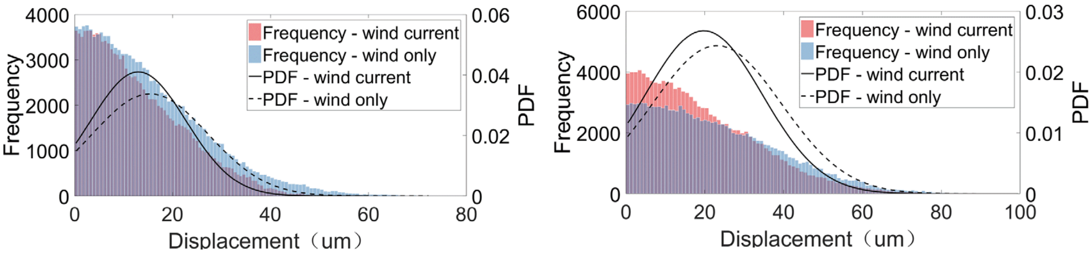
a. STD displacement versus wind speed b. STD displacement versus periods

Figure 6 Standard deviation of displacement of tower model under wind only, wave only and wind-wave

For loading case of wind-current, the current velocities are respectively decided at 0.3m/s, 0.5m/s, 0.8m/s and 1.1m/s and wind speeds are respectively set at 7.5m/s, 11m/s, 20m/s and 25m/s. The estimated probability density function of the displacements at point C under wind-current and wind only at wind speeds of 7.5m/s, 11m/s, 20m/s and 25m/s are described in Figure 7. The frequency in these figures is the number of any displacement value of the tower under various loading states. According to Figure 7a to 13d, the PDF distribution at the loading cases of wind-current and wind only move closer each other with the wind speed increases. The displacements responses of tower under the loading states of wind-current vary in the range of 0mm to 25mm whereas those of tower under the loading states of wind only range only between 0mm and 8mm as shown in Figure 7a. For the loading case at the wind speed of 11m/s, their displacement distributions under wind-current and wind only uniformly range between 0mm and 20mm as shown in Figure 7b. The PDFs of displacement responses of the tower under the loading cases of wind-current and wind only move closer with wind speed increases according to Figures 7c and 7d. Therefore, a similar tendency can be observed that current can only affect the dynamic responses of the tower at low wind speed whereas wind can control the dynamic responses of the tower with wind speed increases.



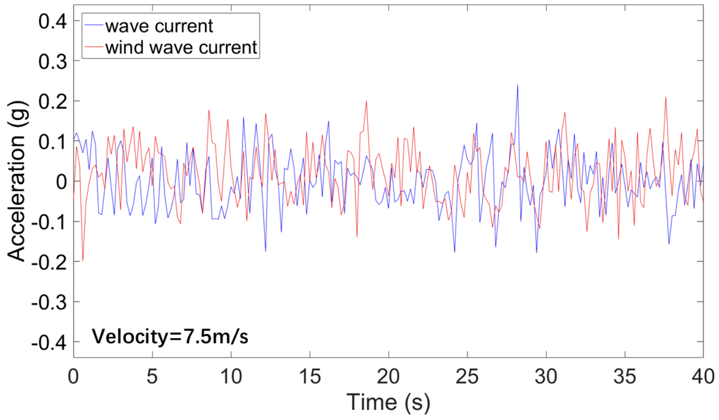
a. Velocity=7.5m/s b. Velocity=11m/s



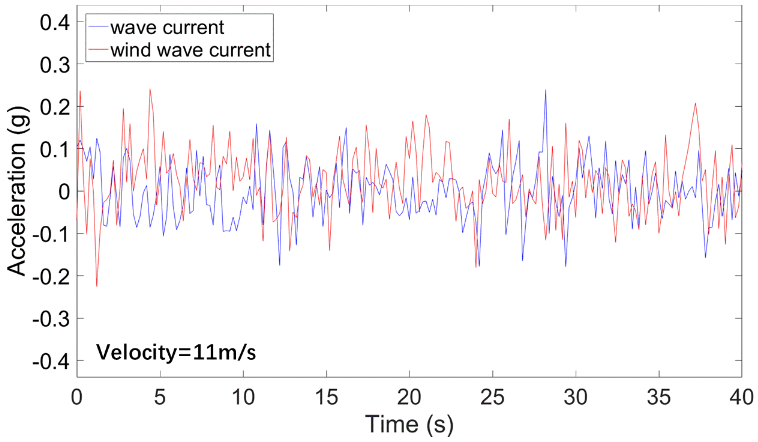
c. Velocity=20m/s d. Velocity=25m/s

Figure 7 Probability characteristics of the displacements at point C under wind-current and wind only at various wind speeds (Current speed =1.1m/s)

For the loading states of wind-wave-current, it can be considered as a combination loading state to compare with dynamic responses of tower model under loading state of wind only. For the wind-wave-current loading state, wind loadings are decided at 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 firstly run at a stable state and then current field is output stably and finally wave field is made by using wave maker.



a.



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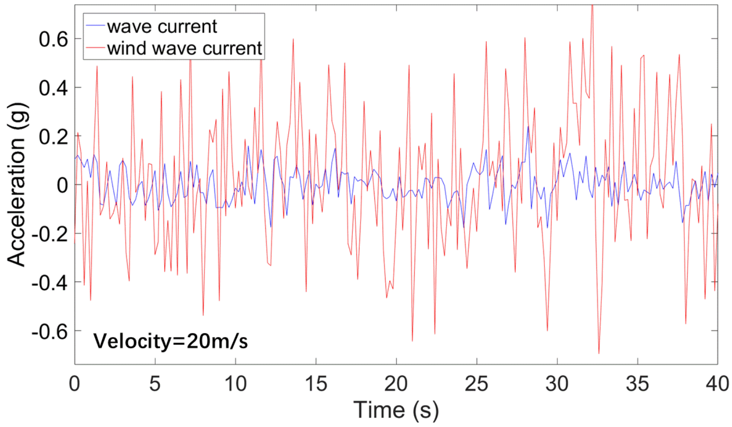


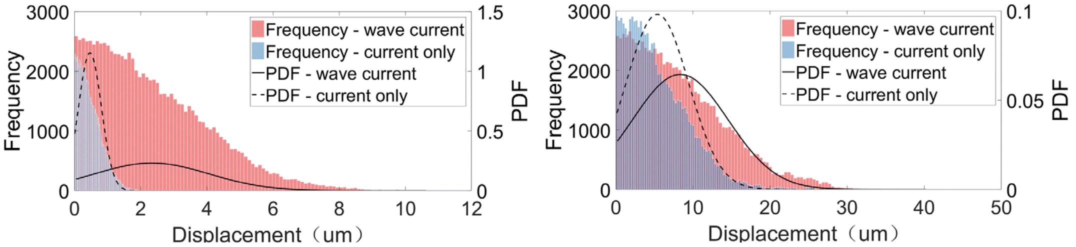
c.

Figure 8 Acceleration responses of tower model under wind-wave-current and wave-current loading states

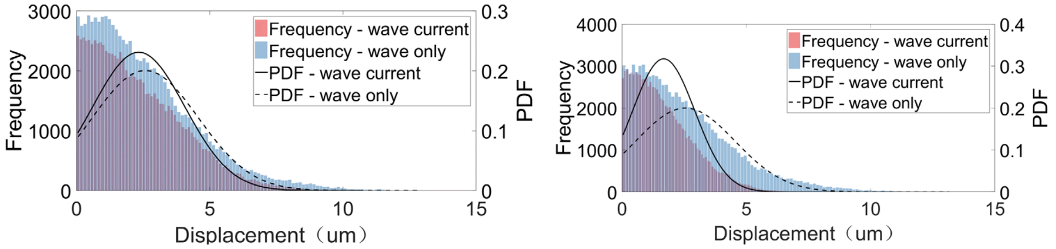
Acceleration responses of tower model under wind-wave-current and wave-current loading states at wind speed of 7.5m/s, 11m/s and 20m/s when current speed is 0.3m/s and wave period is 0.5s can be described in Figure 8. For the loading case at wind speed of 7.5m/s, the acceleration responses of tower model under wind-wave-current coincided with those of tower model under wave-current as shown in Figure 8a, then the acceleration responses of tower model under wind-wave-current are slightly greater than those of tower model under wave-current with wind speed increases from 7.5m/s to 11m/s according to Figure 8a and 8b. Therefore, it can be concluded that the combination of wave-current can dominate under the loading states at a low and medium wind speed. For a wind speed of 20m/s, the effect of wind loading is obviously enhanced as acceleration amplitudes of tower model under wind-wave-current are greater than those of tower under the loading states of wave-current. Therefore, the combination action of wave and current can only affect dynamic responses of tower model in a low and medium wind speed, for a strong wind speed, wind still can control the dynamic responses of the tower.

3.2 Wave and current

For the loading states of wave and current, these loading states including wave only, current only and wave-current are considered to study the effect of wave and current on the dynamic responses of tower model. In this loading case, the current speeds are decided at 0.3m/s, 0.5m/s, 0.8m/s and 1.1m/s and wave periods are set at 0.5s, 0.75s, 1s and 1.25s.



a. Velocity=0.3m/s b. Velocity=1.1m/s



c. Period=0.5s d. Period=1.25s

Figure 9 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)

Figure 9 describes that 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. 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 tower model under wave-current ranges in a wider displacement amplitude than that of tower model under current only as shown in Figure 9a, which means that the wave loadings dominate the structural responses of the tower at this low current speed.

For the loading case at current speed of 1.1m/s, the displacement amplitudes of tower model under wave-current and current only increase whereas the probability functions move closer, which can be found that current field can control significantly the dynamic response of the tower model at current speed of 1.1m/s. According to Figures 9c and 9d, the PDF value of displacement responses of tower model under wave only can always cover that of tower model under current-wave with the wave period increases from 0.5s to 1.25s, the two PDFs only move slightly each other which indicated that wave period increase could not affect very significantly the dynamic responses of tower model under wave-current loading state.

4. Numerical study

4.1 Loadings

In the marine environments, the offshore wind turbine towers during the erection stage are subjected to wind, current and wave loadings. Therefore, in this paper, the weight and bending moment of wind turbine on the top of the tower and horizontal force of wind loadings applied to wind turbine blades are not considered.

4.1.1Wind and current loading

For wind loading, it can be considered to be pressure around the tower wall. However, the wind tunnel can be set to create uniform wind field at different wind speeds. Therefore, to apply wind pressure to the tower model, the wind pressure on the tower model is related to the wind speed based on the Bernoulli equation as follows:

$$P_w = 0.5\rho_a v_a^2 \tag{1}$$

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

According to BS EN 1991-1- 4 (1991), the external wind pressure can be distributed in different profiles on the circular cylinder for various Reynolds numbers when the tower is surrounded by wind field. Reynolds number can be given in the equation (2):

$$R_e = vD/\mathbf{n} \tag{2}$$

Where R_e is Reynolds number, v is fluid speed, D is diameter of tower, $\mathbf{n}$ is kinematic viscosity of fluid. With reference to the current loading, this is transferred into pressure according to the Bernoulli equation:

$$P_c = 0.5\rho_w v_c^2 \tag{3}$$

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

4.2.2 Wave loading

For wave loading, it can be obtained by the Morrison's equation as the offshore wind turbine tower is a slender cylindrical structure in the sea. According to Morrison's equation (Morison, 1950),

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

Where wave moves in x-direction as shown in Figure 2, a and u is acceleration and velocity of undisturbed wave in x-direction, respectively. C_M and C_D are respectively mass coefficient and 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) (Newman, 1997):

$$a = \omega^2 A \frac{coshk(y+h)}{sinhkh} \cos(\omega t - kx) \tag{5}$$

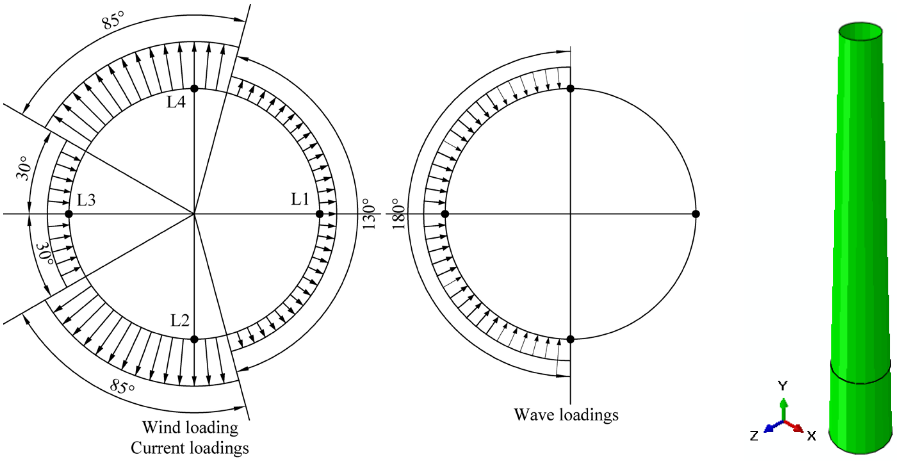
$$u = \omega A \frac{coshk(y+h)}{sinhkh} \sin(\omega t - kx) \tag{6}$$

$$\lambda = \frac{g}{2\pi} T^2 tanh \frac{2\pi}{\lambda} h \tag{7}$$

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

4.2 Validation of the numerical model

The wind turbine tower model is created by the finite element software ABAQUS (2008). The S4R shell element is employed to create the tower wall. The support of the tower is considered as fixed on the bottom of the tower. The tower model is manufactured by Q235 steel in the test. Its density and elastic modulus are respectively 7.85g/cm^3 and 206GPa and Poisson's rate is 0.3. Wind, current and wave loading profile of offshore wind turbine tower are shown in Figure 10. In this model, as wind and current loadings are considered to be similar, the wind loading can be simplified in accordance to the inventory data (ENV 1991-01-04, 1991; Hu et al., 2014) and the current loading can be simplified as shown in Figure 10. In this experiments, the wind speed is 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, which is less than 2.0×10^5. The current speeds can vary 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 (Hu et al., 2014; Roshko, 1961), 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 are respectively decided to be 60°, 85°, 130° and 85° in this loading states as shown in Figure 10. The wind pressure is simplified into uniform pressure along the tower height over the water level as wind field is applied as one constant velocity step by step. Whereas the current pressure also is considered as uniform pressure along the tower height under the water level. For the wave loading, it should be periodic pressure applied on the half section of tower wall under the water level as shown in Figure 10.



a. Wind, current and wave loading profile b. FE model of the tower

Figure 10 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 can be calculated by the equations (1 to 7), therefore, the displacement responses at point C of the tower model under wind, current and wave loadings can be obtained via the numerical model. Figure 11 shows that the experimental and numerical results of displacement responses of the tower model at point C. It can be found that a good agreement between numerical and experimental results has been achieved. Therefore, the numerical model can be employed to support the design of offshore wind turbine tower in engineering practice.

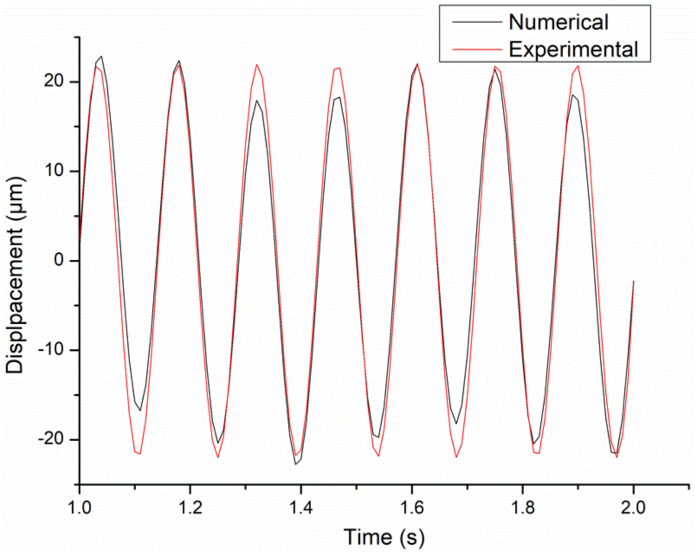


Figure 11 Comparison of time histories of displacement responses of the tower model at point C

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 at the water depth of 0.27m 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.

A numerical model to simulate the structural responses of the tower model under wind, wave and current is performed. The numerical model of offshore wind turbine tower under wind, wave and current is validated by comparing with the experimental results. Therefore, the FE model can be employed to conduct the effect of direction angle between wind and current on the structural responses of the tower model.

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References

1. Xiong Liu, Cheng Lu, Gangqiang Li, Ajit Godbole, Yan Chen., 2017. Tower load analysis of offshore wind turbines and the effects of aerodynamic damping. The 8th International Conference on Applied Energy - ICAE2016. Energy Procedia 105: 373-378.
2. Haoran Li, Zhiqiang Hu, Jin Wang, Xiangyin Meng., 2018. Short-term fatigue analysis for tower base of a spar-type wind turbine under stochastic wind-wave loads. International Journal of Naval Architecture and Ocean Engineering. Volume 10, Issue 1, Pages 9-20.
3. Sungmoon Jung, Sung-Ryul Kim, Atul Patil, Le Chi Hung., 2015. Effect of monopile foundation modeling on the structural response of a 5-MW offshore wind turbine tower. Ocean Engineering 109: 479-488.
4. J. Feliciano, G. Cortina, A. Spear, M. Calaf., 2018. Generalized analytical displacement model for wind turbine towers under aerodynamic loading. Journal of Wind Engineering & Industrial

Aerodynamics 176:120-130.

5. N. Tziavos, H. Hemida, N. Metje, C. Baniotopoulos., 2018. Non-linear Finite Element Analysis of Grouted Connections for Offshore Monopile Wind Turbines, Ocean Engineering 171: 633-645.
6. Wonsul Kim, Jin-Hak Yi, Jeong-Tae Kim, Jae-Hyung Park., 2017. Vibration-based structural health assessment of a wind turbine tower using a wind turbine model. 6th Asia Pacific Workshop on Structural Health Monitoring, 6th APWSHM. Procedia Engineering 188:333-339.
7. Robert Fontecha, Bettina Henneke, Frank Kemper, Markus Feldmann., 2017. Aerodynamic properties of wind turbine towers based on wind tunnel experiments. X international conference on structural dynamic. EURODYNA 2017. Procedia Engineering 199: 3121-3126.
8. M. Zendehbad, N. Chokani, R.S. Abhari., 2017. Measurements of tower deflections on full-scale wind turbines using an opto-mechanical platform. Journal of Wind Engineering & Industrial Aerodynamics 168: 72-80.
9. Karimirad, M., Moan, T., 2012. Wave-and wind-induced dynamic response of a spar-type offshore wind turbine. Journal of waterway, port, coastal, and ocean engineering, 138(1), 9-20.
10. Amirinia, G., Jung, S., 2017. Buffeting response analysis of offshore wind turbines subjected to hurricanes. Ocean Engineering, 141, 1-11.
11. Sun, C., 2018. Mitigation of offshore wind turbine responses under wind and wave loading: Considering soil effects and damage. Structural Control and Health Monitoring, 25(3), e2117.
12. Kan Ye, Jinchen Ji., 2019. Current, wave, wind and interaction induced dynamic response of a 5MW spar-type offshore direct-drive wind turbine, Engineering Structures 178:395-409.
13. Arundhuti Banerjee, Tanusree Chakraborty, Vasant Matsagar, Martin Achmus., 2019. Dynamic analysis of an offshore wind turbine under random wind and wave excitation with soil-structure interaction and blade tower coupling. Soil Dynamics and Earthquake Engineering 125: 105699.
14. Kai Wei, Sanjay R. Arwade, Andrew T. Myers, Vahid Valamanesh., 2016. Directional effects on the reliability of non-axisymmetric support structures for offshore wind turbines under extreme wind and wave loadings. Engineering Structures 106: 68-79.
15. M. Philippe, A. Babarit, P. Ferrant., 2013. Modes of response of an offshore wind turbine with directional wind and waves. Renewable Energy 49:151-155.
16. Lin Chen and Biswajit Basu., 2018. Fatigue load estimation of a spar-type floating offshore wind turbine considering wave-current interactions. International Journal of Fatigue 116: 421-428.
17. Chao Sun, Vahid Jahangiri., 2019. Fatigue damage mitigation of offshore wind turbines under real wind and wave conditions. Engineering Structures 178: 472-483.
18. Piguang Wang, Mi Zhao, Xiuli Du, Jingbo Liu, Chengshun Xu., 2018. Wind, wave and earthquake responses of offshore wind turbine on monopile foundation in clay. Soil Dynamics and Earthquake Engineering 113: 47-57.
19. Enzo Marino, Claudio Borri, Udo Peil., 2011. A fully nonlinear wave model to account for breaking wave impact loads on offshore wind turbines. Journal of Wind Engineering & Industrial Aerodynamics. 99: 483-490.
20. Nianxin Ren, Zhe Ma, Baohua Shan, Dezhi Ning, Jinping Ou., 2019. Experimental and numerical study of dynamic responses of a new combined TLP type floating wind turbine and a wave energy converter under operational conditions. Renewable Energy. DOI: https://doi.org/10.1016/j.renene.2019.11.095.
21. ENV 1991-01-04: Actions on structures, CEN, Brussels 1991.
22. Morison JR, Johnson JW, Schaaf SA., 1950. The force exerted by surface waves on piles. Journal

of Petroleum Technology, 2(5): 149-154.

23. Newman JN. Marine Hydrodynamics [M]. Cambridge: The MIT Press. 1977.
24. ABAQUS/Standard and ABAQUS/Explicit-Version 6.8-1. Abaqus Theory Manual, Dassault System. 2008
25. Hu, Y., Baniotopoulos, C.C., Yang, J., 2014. Effect of internal stiffening rings on the structural response of steel wind turbine towers, Engineering Structures 81: 148-161.
26. Roshko A., 1961. Experiments on the flow past a circular cylinder at very high Reynolds number. Journal of Fluid Mechanics, 10, 345-356.