JREE: Vol. 6, No. 1, (Winter 2019) 8-14

Journal of Renewable Energy and Environment

Journal Homepage: www.jree.ir

Research Article

Effect of Platform Surge Motion on the Performance of 5MW NREL Offshore Floating Wind Turbine

Saeed Karimian Aliabadi*, Sepehr Rasekh

Department of Aerospace Engineering, Tarbiat Modares University, Tehran, Iran.

PAPER INFO

Paper history:
Received 08 June 2019
Accepted in revised form 21 October 2019

Keywords:
Offshore Floating Wind Turbine
Pitch Angle Control System
Platform Surge Motion
Unsteady Aerodynamic

ABSTRACT

In this study, an unsteady aerodynamic simulation is performed to realize the influences of platform surge motion on the aerodynamic performance of a high capacity offshore floating wind turbine. A dynamic model with pitch angle control system is utilized to propose a more realistic model of wind turbine and also achieve the rated condition of the rotor. The transient effect of platform surge motion on power coefficient, thrust coefficient and blade pitch angle also is investigated. The 5 MW NREL wind turbine is selected for the simulations. The unsteady aerodynamic model contains unsteady blade element momentum method, dynamic stall and dynamic inflow models. The in-home aerodynamic code and the control system model are implemented in MATLAB/SIMULINK software. It is revealed that reduction in mean power coefficient at tip speed ratios less that 7 is expected by amount of 12-15 % at surge amplitude of 2m and frequency of 0.1 Hz. For high tip speed ratios, the trend is reverse with respect to fixed-platform case. The mean thrust coefficient is also reduced for many tip speed ratios with maximum loss of 32 %. The mean blade control pitch angle is increased due to the surge motion. Since the influence of changing amplitude and frequency of disturbances depends on the tip speed ratio, therefore the special bound of this parameter is being proposed.

1. INTRODUCTION

Due to higher potential of wind sources at sea regions, using offshore wind turbines have been intensely increased. Although the installation of offshore wind turbines is more complicated and expensive than onshore ones, the availability of space and fewer complaints about noise limitation make them interesting to use. Statistics shows that the mean capacity of offshore farms has been boosted about 15.4 % in 2016. Offshore wind turbines can be installed with fixed foundation or floated platform. The later one is proper for deep sea regions. The offshore floating wind turbines (OFWT) can move due to the sea waves and currents. Therefore, the aerodynamic of rotor become complicated since the rotor also translate or rotate with floated platform.

In the recent years, exploring the effects of platform motion have been investigated by using numerical and semi-empirical methods. The wave induced platform motions comprise of three translational (Heave, Sway, Surge) and three rotational (Roll, Pitch, Yaw) components. These motions can be happened either individually or together, combination of translational and rotational motions. The present study concentrates on the platform translational surge motion as a significant input. Fig. 1 indicates the overview of disturbed-OFWT, and also the global coordinate of OXYZ, which is fixed to the beginning of the tower. The orientation of forward and backward movements also is presented.

Vaal et al. [1] explored the effects of platform surge motion on the induced velocity due to wake region and also thrust variation of wind turbine rotor. The performance of blade element momentum (BEM) theory coupled with a dynamic inflow model is also examined. Results show that the combination of BEM and dynamic wake models can predict the unsteady aerodynamic behavior of a disturbed-OFWT.

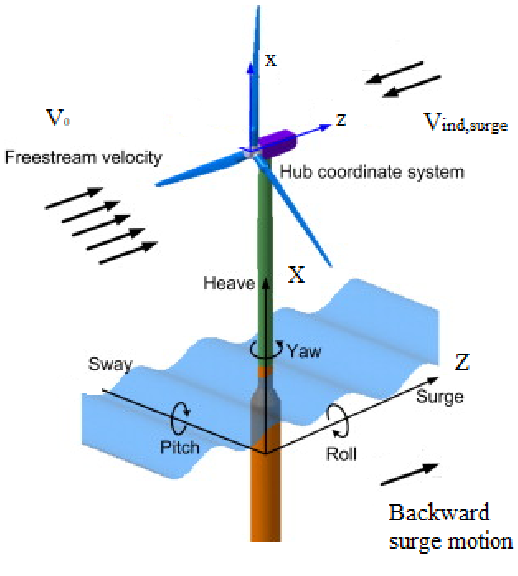


Figure 1. Schematic of disturbed-OFWT, backward platform surge motion.

Farrugia et al. [2] investigated the effects of wave-induced motions of a OFWT using experimental approach. Free-wake vortex method also was utilized for numerical simulation. The purpose was to assess the capabilities of vortex base models. The result reveals high amplitude variation of power coefficient at high tip speed ratios (TSRs) both in experimental and numerical approaches.

Wen et al. [3] also have explored the effects of surge motion on the performance of NREL wind turbine using free vortex method. The effects of pitch angle control system were

---

*Corresponding Author's Email: karimian@modares.ac.ir (S. Karimian Aliabadi)

ignored. It is shown that as the reduced frequency increases, the mean extracted power decreases at low TSRs.

Tran et al. [4] have studied the influence of surge motion on the aerodynamic of OFWT at TRS=7. The NREL 5 MW was selected as the baseline wind turbine for all the simulations. Different aerodynamic methodologies were used for predicting the effect of surge motion, such as CFD and unsteady blade element momentum (UBEM). One of the deductions from this paper is that UBEM method is a reliable method although the computational cost is suitable.

Due to the presence of waves and currents in the sea regions and thus the extra motion of wind turbine, this research is performed to find out the influences of platform surge motion on the OFWT performance. The surge motion is chosen since it affects the performance of OFWT more than heave and sway motions.The proposed aerodynamic model consists of UBEM, Leishman-Beddoes (L-B) dynamic stall and dynamic wake models. The baseline pitch control system is coupled with aerodynamic model to maintain the rated condition.

Based on the literature review, most of the related aerodynamic analysis had been done before on the OFWT, ignored the pitch control system while it will be shown that the pitch control system should be considered to perform an accurate unsteady simulation. This study will go beyond of rated condition via analysis in the presence of pitch control system.

2. UNSTEADY AERODYNAMIC MODEL

The unsteady aerodynamic modeling is performed by using a combination of UBEM method with dynamic stall and dynamic wake models. The models are capable of capturing most of the unsteady influences as there are widely used in the previous researches. In the following, the UBEM method and other unsteady aerodynamic models are reviewed briefly. Then the results will be presented.

2.1. UBEM

The UBEM method is used the theory that proposed by ref. [5]. In the blade element momentum theory, the 1-D momentum theory and strip theory are used together. In this method, the assumption of finite number of blades is corrected by using Prandtl's tip loss factor [6]. In UBEM the value of induced velocity is considered at each time step for all sections [5]. The effect of hub [5] and yaw misalignment [7] will also be considered in our code. In order to add the effect of platform motion to UBEM method the induced velocity due to the platform movement will be added to the model. Therefore, the relative velocity V_{rel} at surge motion case can be expressed as the following equation:

$$V_{rel} = \begin{pmatrix} V_{0_x} \\ 0 \\ V_{0_z} \end{pmatrix} + \begin{pmatrix} 0 \\ -r\omega\cos(\theta_{cone}) \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ w_y \\ w_z \end{pmatrix} + V_{ind,surge} \qquad (1)$$

where $V_{ind,surge} = \begin{pmatrix} 0 \\ 0 \\ \dot{Z}_s \end{pmatrix}$

In which V_{0_x}, V_{0_z}, r and ω are x-direction of free stream velocity, z-direction of free stream velocity, radius of blade section and rotational velocity of the rotor. It should be noted that OXYZ is the local coordinate for rotor blades, as shown in Fig. 1. Where the displacement of OFWT at platform surge motion condition Z_s can be expressed as:

$$Z_s(t) = Amp \, . sin(2\pi f t) \qquad (2)$$

The time-varying surge displacement and induced velocity due to the corresponding platform motion at OFWT hub are shown in Fig. 2 at *f*=0.1 Hz.

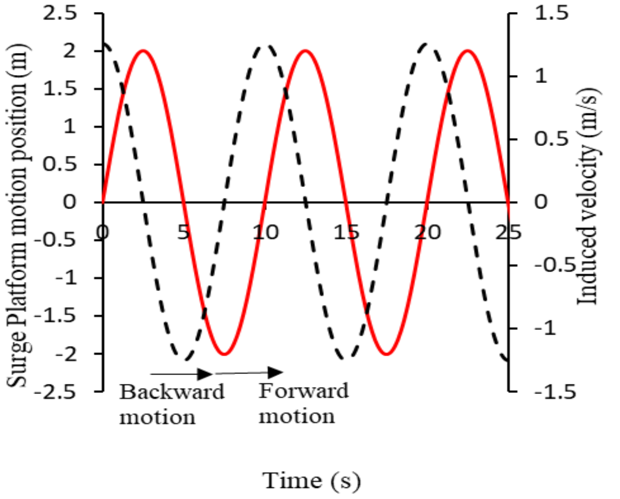


Figure 2. Variation of hub position and induced velocity due to surge motion (*f=0.1 Hz*).

2.2. Dynamic wake and dynamic stall models

To consider the time delay due to unsteady forces, a dynamic wake model should be utilized. Using this model to capture the time behavior of aerodynamic loads when the thrust is altered by changing pitch angle of blades is crucial. The method is same as the presented by Øye [8] which is a common used dynamic wake model.

Dynamic stall can be happened at inboard part of the wind turbine blades. This phenomenon initiates with the formation of a vortex at the leading edge that sheds along the chord of airfoil from leading edge to trailing edge [9]. This vortex causes that the maximum lift coefficient increases at dynamic stall situation, which is higher than static maximum lift coefficient [10]. In the following, the Leishman-Beddoes (L-B) [11] model is selected to predict the influences of dynamic stall phenomena since it is widely used and validated by researchers [12, 13].

3. BASELINE WIND TURBINE AND CONTROL SYSTEM

The NREL 5 MW horizontal axis wind turbine is used as the baseline wind turbine here. [14]. The rotor contains 3 blades with 63m length. The rated wind speed and rotational velocity is 11.4 m/s and 12.1 rpm, respectively. Two types of power control system are installed for the baseline wind turbine. The first one controls the generator torque at below rated condition. The second control system is activated in the situation that the wind turbine passes the rated condition. In the latter system, the pitch controller regulates the pitch angle of the blades in order to maintain the rated power the wind turbine.

The baseline pitch controller which has been developed by Jonkman [14] is gained for the current simulation. The control system is modeled in SIMULINK software. Dynamic of the rotor is based on one-mass model using an equivalent inertia. The pitch control system is a PI (Proportional-Integrator) [15] controller as:

$$\theta_{pitch}(t) = K_P(\theta_{pitch})e(t) + K_I(\theta_{pitch})\int_0^t e(\tau)d\tau \qquad (3)$$

$$e(t) = \omega_{gen} - \omega_{rated}$$

The pitch angle will be applied at the hub via an actuator for all the blades simultaneously.

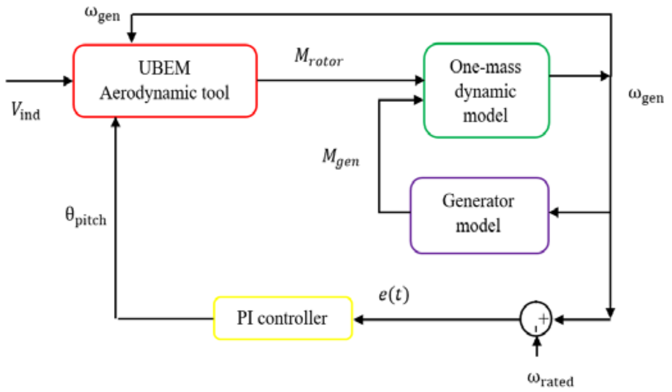


Figure 3. Pitch control system implementation.

4. VALIDATION

In following sections, two types of representation of the results are chosen. Firstly, time-averaged parameters are calculated and reported against different tip speed ratios. These parameters are power and thrust coefficients and pitch angle estimated by pitch control. Power coefficient, thrust coefficient [16] and TSR can be calculated as:

$$C_p = \frac{\text{Power}}{\frac{1}{2}\rho V_0^3 \pi R^2} \qquad (4)$$

$$C_T = \frac{\text{Thrust}}{\frac{1}{2}\rho V_0^2 \pi R^2} \qquad (5)$$

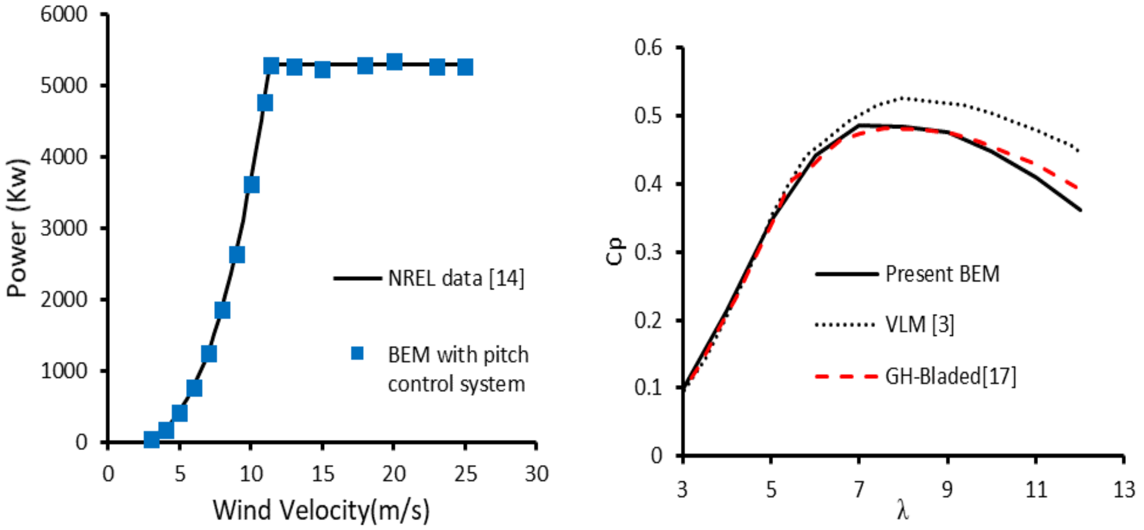
$$\lambda = \frac{R\omega}{V_0} \qquad (6)$$

The averaged power and thrust coefficients can be defined as:

$$C_{p,ave} = \frac{\frac{1}{T}\int_0^T \text{Power}(t)dt}{\frac{1}{2}\rho V_0^3 \pi R^2} \qquad (7)$$

$$C_{T,ave} = \frac{\frac{1}{T}\int_0^T \text{Thrust}(t)dt}{\frac{1}{2}\rho V_0^2 \pi R^2} \qquad (8)$$

Secondly, the time marching results will be presented to fully understand the effects of platform motion on performance of the offshore wind turbine. To show the validity of the results, the steady data of the wind turbine [14] is utilized to indicate the accuracy of BEM code and pitch control system. Moreover, additional steady state results of same the wind turbine [3, 17] is used in validation of the present BEM code. The results of the simulation are shown in Fig. 4.



(a)

(b) $V_0 = 6\frac{m}{s}$, $\theta_{pitch} = 0$

Figure 4. a) Power against wind velocity (with pitch control system), b) Power coefficient against λ for land-based NREL wind turbine.

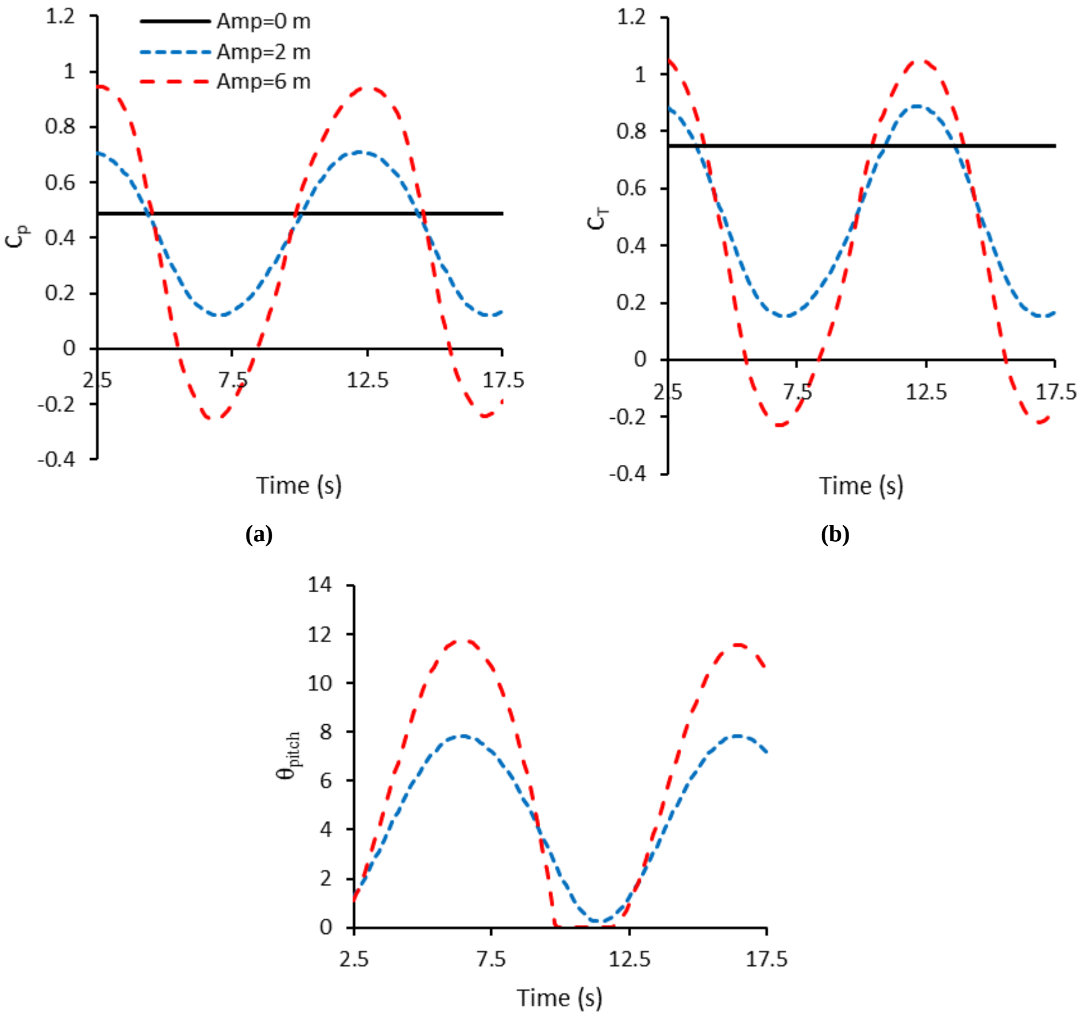
5. RESULTS AND DISCUSSION

The effect of surging motion applied to the platform as the significant input, is being investigated in this part. In the following, these results have been summarized using both averaged and time-marching results. In each section, the time averaged performance (disturbed-OFWT) is being compared with the steady-state performance which is assumed to be available in the land-based condition. The latter case describes the operation of a fixed OFWT.

5.1. Platform surge motion

In this part, the effects of platform surge motion on the performance of 5 MW OFWT will be investigated. Firstly, a comparison between disturbed-OFWT and fixed-platform is presented. Then the effect of different surge amplitudes will be studied in more details. The surge motion is independent of rotation center position of the overall OFWT, because the movement of the OFWT is defined as a sine function, the platform type is not important in this aerodynamic analysis. It should be mentioned again that the simulations were performed based on a coupled aerodynamic-pitch control system tool for both disturbed-OFWT and fixed-platform case. The two different platform surge amplitudes employed are Amp=2 m and Amp=6 m. The frequency of surge motion is set to be 0.1 Hz, i.e. *f*=0.1 Hz. The TSR varies from 3 to 9. The case of fixed-platform, here distinguished by Amp=0 m.

To illustrate the first impression of the effect of platform surge motion, Fig. 5 is being referred. It can be seen that the behavior of power and thrust coefficients at disturbed-platform cases are totally different from fixed-platform case. At some phases, these coefficients are more than the fixed-foundation case and in other phases they are less, as shown in Fig. 5 (a), (b). The same trends have been shown in references [3, 4]. These differences cause that the aerodynamic behavior of disturbed-OFWT becomes complicated. The influence of surge motion of OFWT on the pitch angle is also noticeable. As it is depicted in Fig. 5(c), in this case (TSR =7), the control pitch angle of the blades at platform surge motion condition is totally more than the fixed-platform.



(a) **(b)**

(c)

Figure 5. Time-varying aerodynamic characteristics at platform surge motion (*f*=0.1 Hz, Amp=2 m and TSR=7).

5.2. Effect of surge amplitude

The comparison of averaged power coefficient, thrust coefficient and pitch angle between disturbed-OFWT and fixed-foundation cases is represented in fig. 6 for both amplitudes. As shown in Fig. 6(a), the mean power coefficient is decreased at TSR ≤ 7 respect to fixed-foundation wind turbine, while the mean power coefficient is increased for TSR > 7. In references [3, 18], the same trends are reported, although the effect of pitch control system was not considered. Probable reasons of performance difference between OFWT case and fixed-platform, could be summarized as follows:

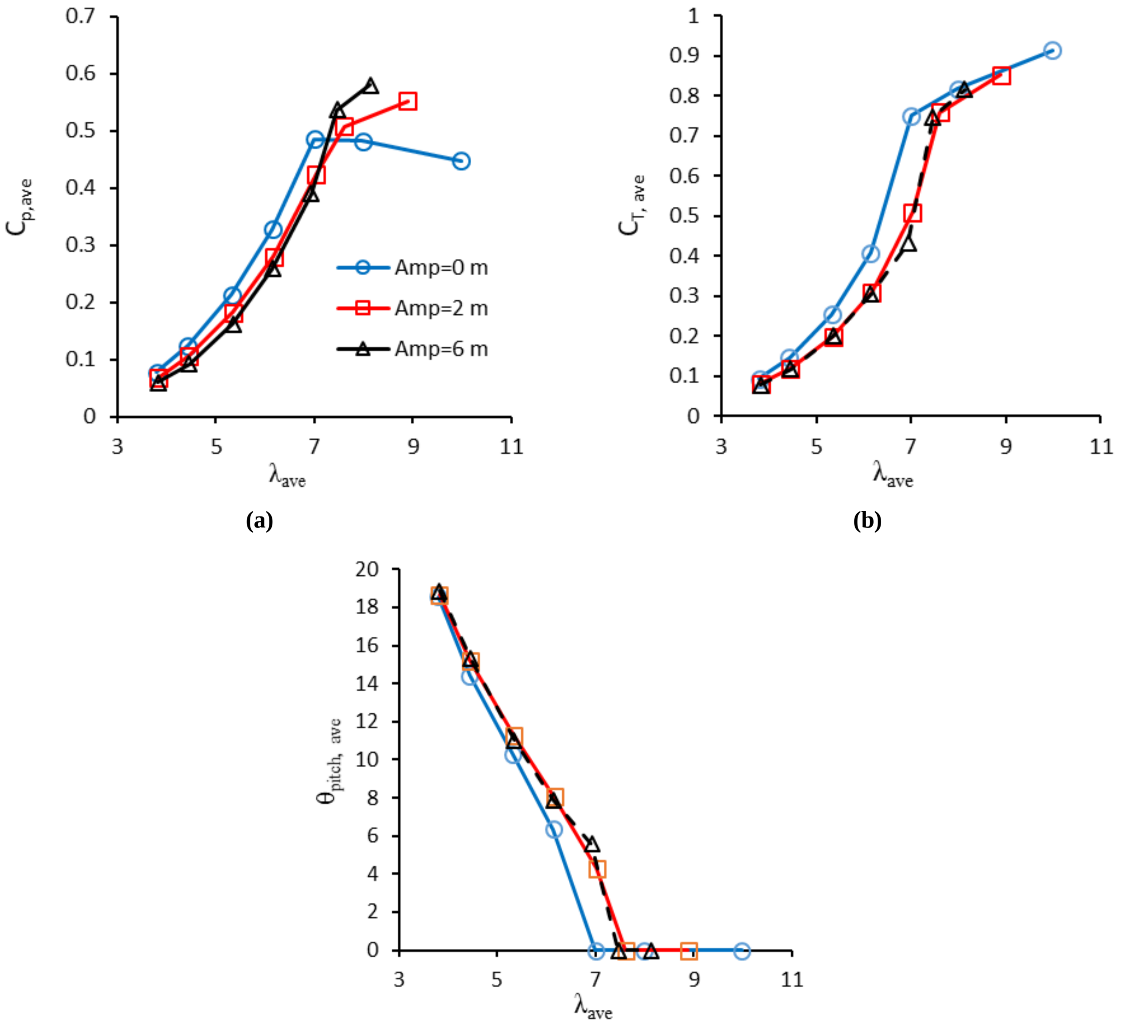
1. The unsteady aerodynamic time delay due to the variation of control pitch angle.
2. reduction in axial induction factor which affect the turbine performance.
3. rising the mean control pitch angle at surge motion.

The percentage of change in power and thrust coefficients at surge condition respect to fixed-platform case is shown in Table 1. Moreover, it is also shown that increasing the surge amplitude, at TSR ≤ 7, would result more reduction in mean power coefficient respect to fixed-platform, while the opposite trend occurs at TSR > 7.

It is depicted in Fig. 6(b) in platform surge motion condition, the mean thrust coefficient decreases, especially at TSR ≤ 7. In the investigation of Wen et al.[3] a slightly reduction of thrust coefficient was detected for $6 < \text{TSR} < 8$. However, in the present study, the more reduction in thrust coefficient for wider range of TSRs is detected. This is due to the presence of pitch control system which affects the aerodynamic performance of OFWT. The positive consequence of mean thrust coefficient reduction is that the OFWT will experience smaller equivalent platform surge motion, since the mean axial force in direction of motion on the OFWT rotor will be decreased. It should be mentioned that the effect of increasing surge amplitude on the thrust coefficient, as it is shown, is not tangible, while a little reduction of thrust coefficient can be seen. Finally, from Fig. 6(c) it can be revealed that the averaged control pitch angle, same as previous study of platform pitch motion, will be increased with respect to fixed-platform condition.

Table 1. Percentage of change in power and thrust coefficients respect to fixed-platform case at different TSRs (surge motion case: *f*=0.1 Hz, Amp= 2 m).

TSR	3.82	4.45	5.35	6.17	7.03	7.21	8.55
$\mathbf{C_{p,ave}}$	-12.76	-13.78	-14.75	-14.5	-12.69	0.7	6.65
$\mathbf{C_{T,ave}}$	-14.13	-17.88	-21.70	-24.05	-32.14	-0.75	0.17

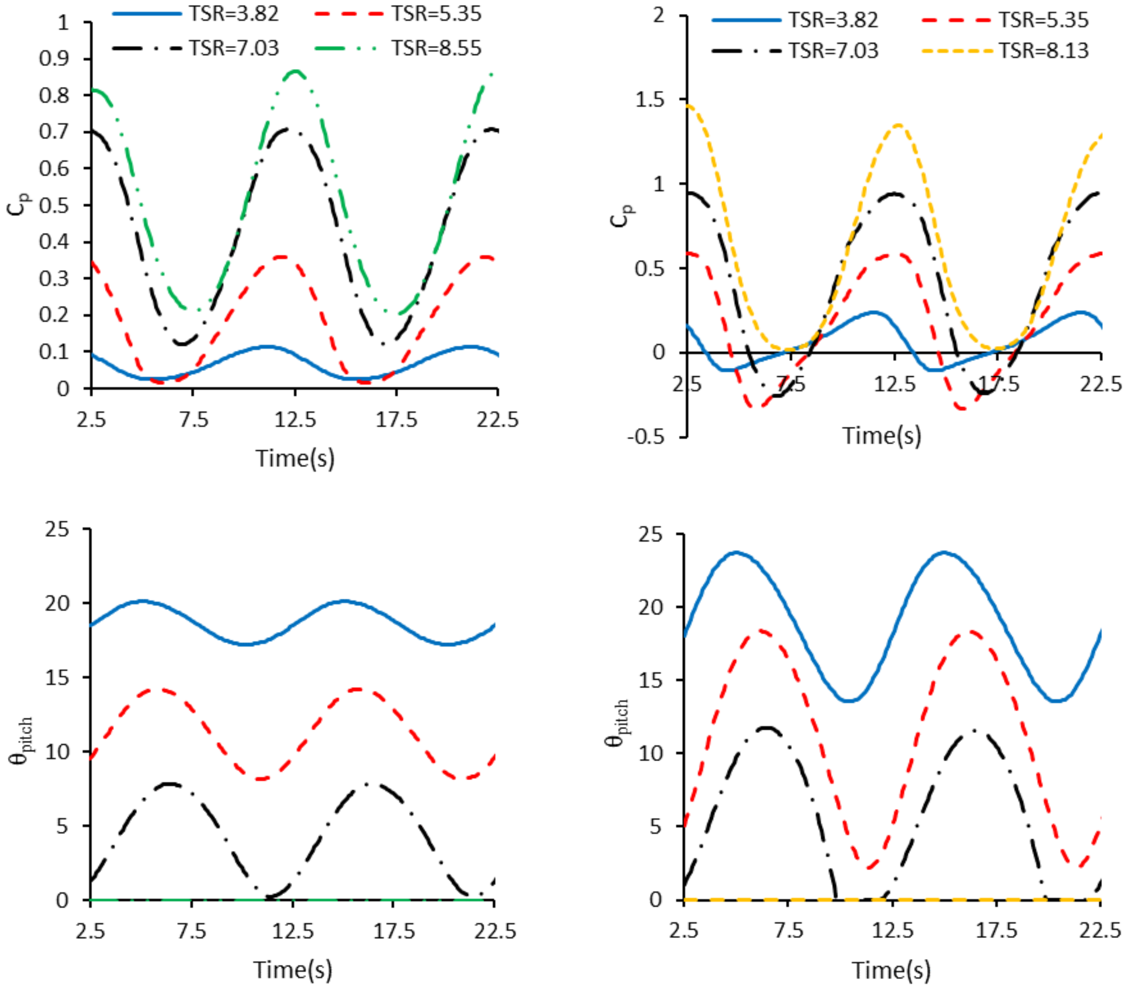


(a) **(b)**

(c)

Figure 6. Mean aerodynamic characteristics aginst TSR at different amplitudes for platform surge motion (*f*=0.1 Hz).

Fig. 7 shows the variation of power coefficient and pitch angle with time for a) Amp= 2m and b) Amp= 6m at *f*=0.1 Hz. It can be seen that the power coefficient would be changed by altering surge amplitude. For instance, the maximum power coefficient at Amp= 6 m is more than Amp= 2 m case for all TSRs. The amplitude of power coefficient variation and therefore the fatigue loads are less at lower TSRs. At some phases, the negative values of power coefficient were obtained, which mostly was occurred at Amp= 6m. Consequently, the performance of the OFWT will be degraded. It also reveals the importance of pitch control system design in order to minimize the variation of power and thrust coefficient and prevent the occurrence of negative power coefficient at high amplitude surge motions. It should be mentioned that at TSR=8.13 the negative values of power coefficient are not observed, which also approves the increase of mean power coefficient respect to fixed-platform in this case.



(a) Amp=2 m **(b)** Amp=6 m

Figure 7. Time-varying aerodynamic characteristics at platform surge motion (*f*=0.1 Hz).

6. CONCLUSIONS

Offshore floating wind turbines experience 6-DOF platform motion due to sea currents. Theses extra motions dramatically alter the performance of wind turbine. Therefore, in the current study, the effect of platform surge motion on the aerodynamic characteristics of a benchmark OFWT was investigated using an unsteady aerodynamic model. UBEM is the core of unsteady simulation with dynamic wake and stall models. The pitch control system is utilized to reach the rated condition of wind turbine rotor which is power output about 5 MW. Accordingly, different amplitudes of surge motion as it will be experienced in the sea condition, have been examined and different tip speed ratios. Some conclude remarks are listed below as:

- Adding the contribution of rotor inertia, generator characteristics and pitch angle control system will improve the unsteady analysis of wind turbine. Also, it provides a more realistic model of a wind turbine, especially in the case of OFWT simulation.
- The platform surge motion significantly affects the aerodynamic characteristics of OFWT. The fluctuations of power coefficient in rated and some under rated conditions, will cause the control action. Therefore, some critical considerations shall be accounted in structural design of OFWT.
- In case of platform surge motion, the mean power coefficient decreases for tip speed ratios less than 7; for instance, in case of Amp=2 m and *f*=0.1 Hz, reduction of mean power coefficient averagely is about 13.6 percent, while it will be increased for high TSRs; for example, at TSR=8.55 is about +6.5 percent.
- The thrust coefficient decreases for almost all the surge oscillations; the maximum reduction occurs at TSR=7 which is about 32 percent.
- The averaged pitch angle effort applied by control system, increases respect to fixed-platform.

7. ACKNOWLEDGEMENT

The authors wish to acknowledge the financial supports from the mechanical department of Tarbiat Modares University.

NOMENCLUTURE

T	Time period
t	Time
V_o	Free stream velocity
$V_{ind,surge}$	Induced velocity of surging motion
V_{rel}	Relative velocity

V_{0_x}	Y-direction wind velocity
V_{0_z}	Z-direction wind velocity
w_y	Y-direction induced velocity
w_z	Z-direction induced velocity
Z_s	Platform surge motion displacement
ω	Rotational velocity of rotor
ω_{gen}	Generator rotational speed
ω_{rated}	Rated rotational speed
ρ	Density
λ	Tip speed ratio
λ_{ave}	Averaged tip speed ratio
θ_{pitch}	Control system pitch angle
Amp	Surge amplitude
C_l	Lift coefficient
C_p	Power coefficient
C_T	Thrust coefficient
$C_{p,ave}$	Averaged power coefficient
$C_{T,ave}$	Averaged Thrust coefficient
f	Surge motion frequency
K_I	Integrator gain
K_p	Proportional gain
L	Overhang length
M_{rotor}	Rotor torque
M_{gen}	Generator torque
r	Radius of each blade section
R	Rotor radius

REFERENCES

1. Vaal, J.D., Hansen, M. and Moan, T.,"Effect of wind turbine surge motion on rotor thrust and induced velocity", ***Wind Energy***, Vol. 17, No. 1, (2014), 105-121. (DOI:10.1002/we.1562).
2. Farrugia, R., Sant, T. and Micallef, D., "Investigating the aerodynamic performance of a model offshore floating wind turbine", ***Renewable Energy***, Vol. 70, No. 1, (2014), 24-30. (DOI:10.1016/j.renene. 2013.12.043).
3. Wen, B., Tian, X., Dong, X., Peng, Z. and Zhang, W., "Influences of surge motion on the power and thrust characteristics of an offshore floating wind turbine", ***Energy***, Vol. 141, No. 1, (2017), 2054-2068. (DOI:10.1016/j.energy.2017.11.090).
4. Tran, T.T. and Kim, D.-H., "A CFD study into the influence of unsteady aerodynamic interference on wind turbine surge motion", ***Renewable Energy***, Vol. 90, No. 1, (2016), 04-228. (DOI:10.1016/j.renene.2015.12.013).
5. Hansen, M.O., Aerodynamics of wind turbines, Routledge, (2015).
6. Glauert, H., Airplane propellers, in Aerodynamic theory, Springer, (1935), 169-360.
7. Snel, H. and Schepers, J., "Joint investigation of dynamic inflow effects and implementation of an engineering method", ***Netherlands Energy Research Foundation ECN***, (1995).
8. Schepers, J., Snel, H. and van Bussel, G., "Dynamic inflow: Yawed conditions and partial span pitch control", ***Netherlands Energy Research Foundation ECN***, (1995).
9. Gupta, S. and Leishman, J.G., "Dynamic stall modelling of the S809 aerofoil and comparison with experiments", ***Wind Energy***, Vol. 9, No. 6, (2006), 521-547. (DOI:10.1002/we.200).
10. Shipley, D.E., Miller, M.S. and Robinson, M.C., "Dynamic stall occurrence on a horizontal axis wind turbine blade", ***National Renewable Energy Lab Golden CO.***, (1995).
11. Leishman, J.G. and Beddoes, T., "A semi empirical model for dynamic stall", ***Journal of the American Helicopter Society***, Vol. 35, No. 3, (1989), 3-17.
12. Rasekh, S., Hosseini Doust, M. and Karimian Aliabadi, S. "Accuracy of dynamic stall response for wind turbine airfoils based on semi-empirical and numerical methods", ***Journal of Applied Fluid Mechanics***, Vol. 11, No. 5, (2018), 1287-1296. (DOI: 10.18869/acadpub.jafm. 73.248.28668).
13. Pereira, R., Schepers, G. and Pavel, M.D., "Validation of the Beddoes–Leishman dynamic stall model for horizontal axis wind turbines using MEXICO data", ***Wind Energy***, Vol. 16, No. 2, (2013), 207-219. (DOI:10.1002/we.541).
14. Jonkman, J., Butterfield, S., Musial, W. and Scott, G., "Definition of a 5-MW reference wind turbine for offshore system development", ***National Renewable Energy Laboratory (NREL)***, (2009).
15. Namik, H. and Stol, K., "Performance analysis of individual blade pitch control of offshore wind turbines on two floating platforms", ***Mechatronics***, Vol. 21, No. 4, (2011), 691-703.
16. Burton, T., Jenkins, N., Sharpe, D. and Bossanyi, E., Wind energy handbook, ***John Wiley & Sons***, (2011).
17. Farrugia, R., Sant, T. and Micallef, D., "A study on the aerodynamics of a floating wind turbine rotor", ***Renewable Energy***, Vol. 86, No. 1, (2016), 770-784. (DOI:10.1016/j.renene.2015.08.063).
18. Micallef, D. and Sant, T., "Loading effects on floating offshore horizontal axis wind turbines in surge motion", ***Renewable Energy***, Vol. 83, No. 1, (2015), 737-748. (DOI:10.1016/j.renene.2015.05.016).