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Research Paper

Evaluation of Turbulence on the Dynamics of Monopile Offshore Wind Turbine under the Wave and Wind Excitations

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Abstract. In recent years, the use of offshore wind turbines has been considered on the agenda of the countries which have a significant maritime boundary due to more speed and stability of wind at sea. The aim of this study is to investigate the effect of wind turbulence on the aero-hydrodynamic behavior of offshore wind turbines with a monopile platform. Since in the sea, the wind turbine structures are under water and structures interactions, the dynamic analysis has been conducted under combined wind and wave loadings. The offshore wind turbines have been investigated under two models of normal and severe wind turbulence, and the results of this study show that the amplitude of fluctuation of dynamic response is increased with increasing amount of wind turbulence, and this increase is not necessarily observed in the mean values of responses. Therefore, conducting the dynamic analysis is inevitable in order to observe the effect of wind turbulence on the structures response.

Keywords: Offshore wind turbine, Wind turbulence, Wind and wave excitations, Monopile

1. Introduction

The use of wind energy as a renewable source and alternative to fossil fuels has a long-term history and is related to the 2nd century of BC in ancient Persia. For the first time, the Iranians were succeeded to circulate the doulab or windlass using wind power and bring water from wells on farms [1]. The growth of generating electricity from new energies was more than the growth of generating electricity from fossil resources for the first time in Europe Union in 2006 [2]. Electricity generation capacity through wind turbines in the world has been increased from 18,000 MW to 92,000 MW from 2000 to 2007. Since 2000, this industry has grown 25% annually and has doubled every three years, and this is on the condition that the global economic growth is not more than one to two percent per year [2].

In recent years, the use of offshore wind turbines has been considered on the agenda for the countries which have a significant maritime boundary due to more speed and stability of wind at sea. Thus, Iran also should benefit from this type of clean and renewable energy as an alternative to the exhaustible fossil fuels in the future due to the hundreds of kilometers of sea border in the south and north of the country.

The offshore wind turbines are influenced by loading sea, such as waves, marine currents, etc. by placement in the marine environment in addition to being exposed to loads caused by wind blowing [3]. Therefore, the behavioral analysis of this structures under combined aerodynamic and hydrodynamic loading is very important. So far, several models have been presented to consider coupled analysis of wave and wind. For instance, Mata et al. investigated the coupled modeling challenges in offshore wind turbine [4]. Then, Karimi Rad and Moan presented a simplified model for the coupled analysis of offshore wind turbine with floating platform [5]. Also Dezvareh et al. modeled the offshore wind turbine with jacket type platform in Simulink based on the equations governing the force generated by wind (blade element momentum theory), force generated from the interaction of water and structures (Morison equation), and investigated the effect of the parameters of wave height and wind speed on the behavior of the offshore wind turbine in addition to vibration control of this structures [6] and [7]. Given that one of the parameters affecting the wind turbines is the amount of wind turbulence, this study deals with the investigation of the effect of wind turbulence based on the existing standards on the dynamic behavior of an offshore wind turbine with a monopile platform.

2. Monopile Type Offshore Wind Turbine

In this study, 5-megawatt turbine designed at America's National Renewable Energy Laboratory (NREL) with a monopile holder platform has been considered. This turbine generates 5 MW rated power and is located in 90 m height above the sea level. The length of each blade is 61.3 m. The monopile holder platform of this turbine is located in depth of 20 m of water which has the diameter 6 m and constant thickness 6 cm [8].

3. The Aero-Hydrodynamic Behavior of Offshore Wind Turbine

As stated before, the behavior of offshore wind turbine under the dynamic loads resulting from wind and wave is interacted and coupled. The modified Morrison equation according to the Eqs. (1), (2), and (3) which considers the effect of the relative motions of structures against water has been used to calculate the wave load and hydrodynamic forces caused by the interaction of water and holder platform of wind turbine.

$$F_{hydro} = F_{Morison} = F_D + F_I \tag{1}$$

$$F_D = 0.5\rho C_D A(v - \dot{u})|v - \dot{u}| \tag{2}$$

$$F_I = \rho B(C_M \dot{v} - (C_M - 1)\ddot{u}) \tag{3}$$

Also the theory of blade element momentum (BEM) is used according to the eqs. (4) and (5) to calculate the wind load and aerodynamic force caused by collision of wind with turbine. Figure 1 presents more details of BEM using in offshore wind turbine analysis.

$$F_{LIFT} = 0.5\rho_{air} V_{rel}^2 c C_l \tag{4}$$

$$F_{DRAG} = 0.5\rho_{air} V_{rel}^2 c C_d \tag{5}$$

According to the above equations, wind flow over the airfoil of blades generates aerodynamic forces of the Lift and Drag. The categories of loading the wind turbine must withstand include static loads (not associated with rotation), steady loads (associated with rotation, such as centrifugal force), cyclic loads (due to wind shear, blade weight, yaw motion)and impulsive loads (short duration loads, such as blades passing through tower shadow and stochastic loads (due to turbulence). These aerodynamic forces on the blades and turbine made up from three main components as follows:

- A rather uniform component that is mostly produced by the average wind speed.
- Periodic forces which are generated by turbine tower shadow, wind shears, blades rotation and non-axial winds
- Turbulent portion of aerodynamic forces with irregular fluctuations.

In the following, it deals with the investigation of different models of turbulence to be considered in the irregular aerodynamic forces.

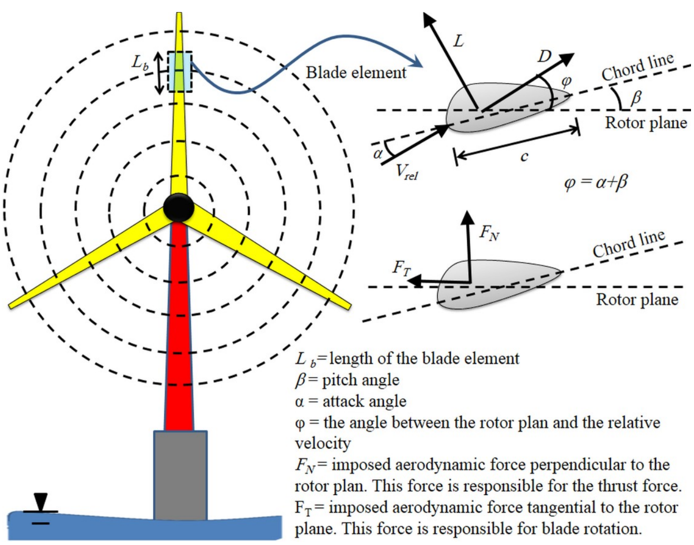

Fig. 1. Aerodynamic forces per BEM theory

4. Wind Turbulence Models

Generally, two models of Normal Turbulence Model (NTM) and Extreme Turbulence Model (ETM) are considered for the wind according to the international standards of design for offshore wind turbines. The value of turbulence coefficients in different wind speeds for these two models are adopted according to Fig. 2. The ETM is generally used in ultimate strength analysis of wind turbines while the NTM is typically applied in normal operational condition or fatigue analysis of wind turbines. In this research, these two turbulence models are just used for comparison to show that wind turbulence has a large influence on its response.

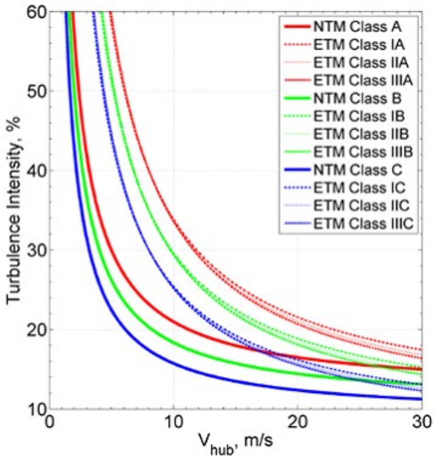

Fig. 2. The changes in turbulence coefficient in terms of wind speed for Normal Turbulence Model and Extreme Turbulence Model [11]

According to Fig. 2, the values of turbulence coefficients for both the NTM and the ETM are reduced by increasing wind speed.

5. Description of modeling and results

The open source code of FAST has been used in order to model and solve aero-hydro dynamic interaction equation of offshore wind turbine. Multiple corrections, such as dynamic inflow, dynamic stall and tip loss in the BEM theory are considered in the open source code (FAST) in this study. Further details are given in [8] and Appendix A. The input parameters of this model are four different combinations of wind and wave loadings. These environmental conditions (EC) are considered in accordance with the Table 1. Since there must be a logical relation between the wave and the wind data, the process of selecting these four environmental conditions is that at first, four different wind speeds are selected, then, according to the prediction the wave parameters from wind data (wave hindcasting equations [12]), the significant wave height and peak wave period corresponding to the given wind speed are calculated. The three-dimensional view of the conducted modeling is observed in Fig. 3.

Table 1. Environmental conditions of wave and wind excitations

	Mean Wind Speed (m/s)	Significant Wave Height (m)	Peak Wave Period (s)
EC1	6.0	0.9	5.0
EC2	10.0	2.5	8.3
EC3	14.0	4.9	11.6
E C4	18.0	8.0	14.9

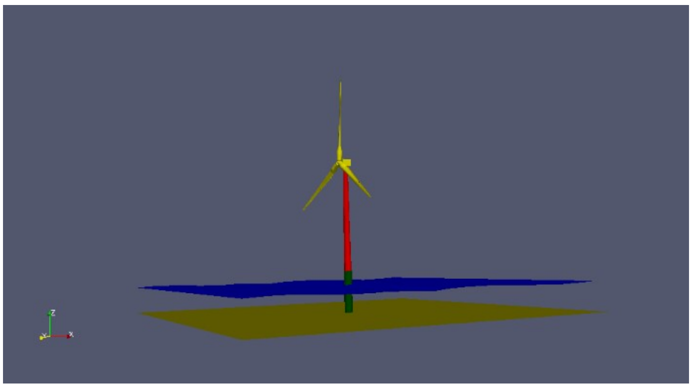

Fig. 3. The three-dimensional view of the model of offshore wind turbine with a monopile platform

To investigate the effect of wind turbulence, two models of the NTM and the ETM were applied according to the international regulations of design of offshore wind turbines for the average wind speeds in the TURBSIM code (Appendix B) which is the subset of the FAST program, and the outputs of time history of the wind speed were calculated according to the diagrams of Fig. 4. Also, in Table 2 and Fig. 5, the statistical parameters of wind speed are compared between two models.

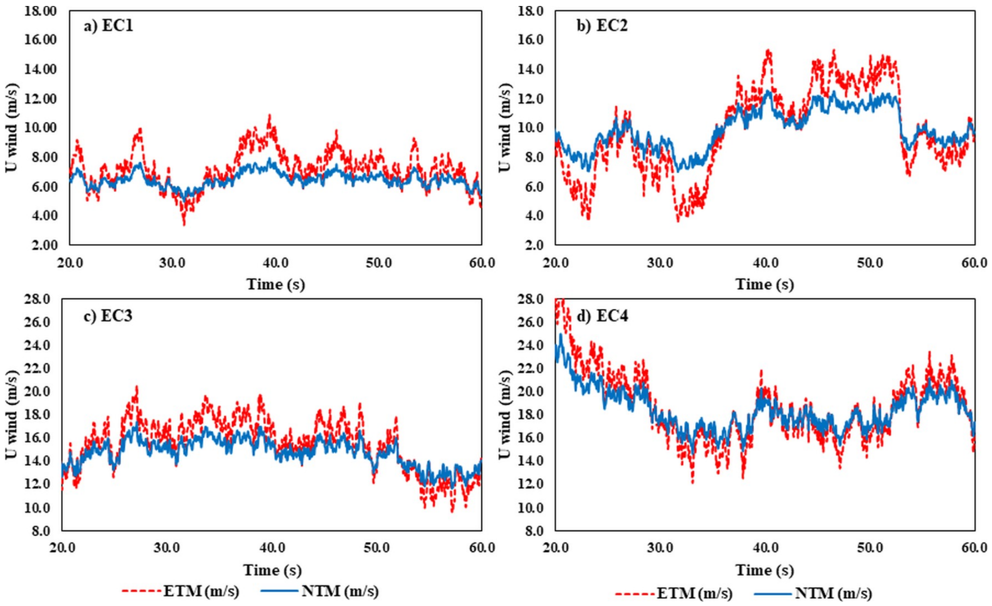

Fig. 4. The time history of the wind speed

Table 2. The statistical values of wind speed (m/s)

	EC1			EC2		
Parameters	σ	μ	max	σ	μ	max
NTM	0.5	6.5	7.9	1.4	9.9	12.6
ETM	1.2	7.2	10.9	3.0	9.8	15.4
Percentage increase (%)	151.2	11.0	37.0	113.4	-1.2	23.0
	EC3			EC4		
Parameters	σ	μ	max	σ	μ	max
NTM	1.2	14.8	17.4	1.8	18.4	25.0
ETM	2.2	15.5	20.5	3.1	18.7	30.1
Percentage increase (%)	89.8	4.7	17.5	73.5	1.7	20.6

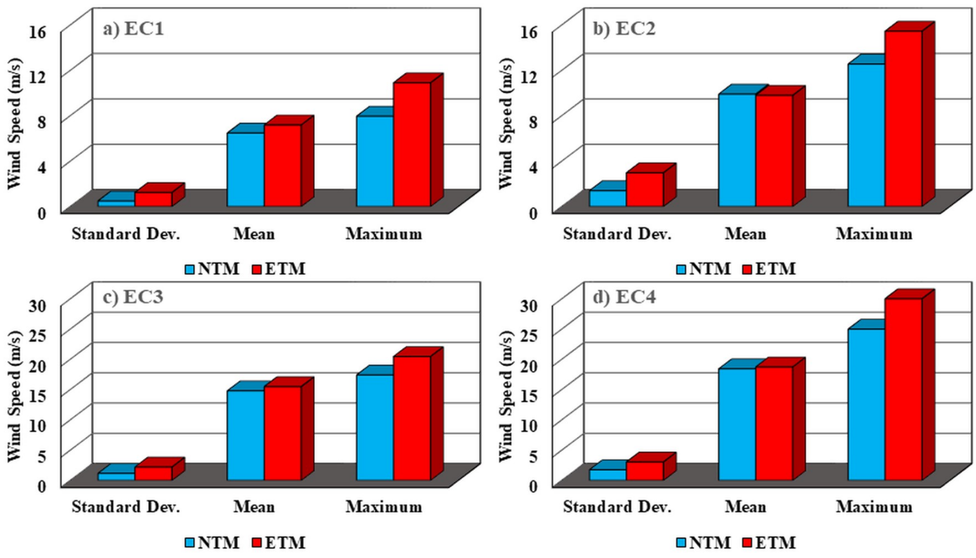

Fig. 5. Parametric comparison of wind speed

In the following, the time history of the wind speed in two models of turbulence is applied to the original model along with the other wave and wind parameters, and the amount of force and aerodynamic moment produced by rotor thrust and rotor torque and also base shear force and over turning moment were calculated as output for comparing two turbulence models.

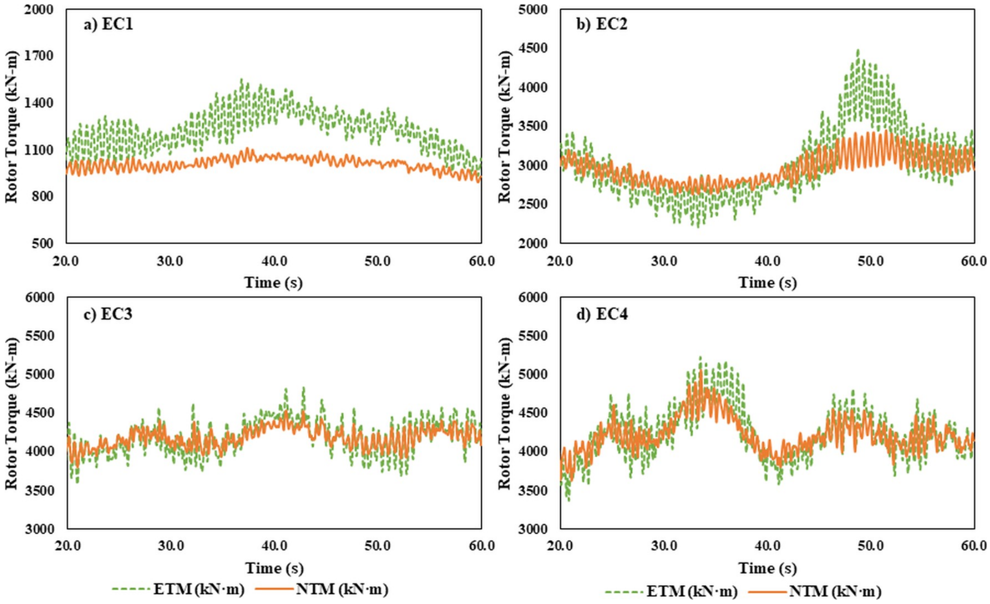

Fig. 6. The time history of the rotor torque

According to Fig. 6, it is observed that the mean values of rotor torque are approximately equal for the two models of turbulence, but the amplitude of fluctuation in ETM is much more than NTM. For more accurate investigation of this issue, the values of maximum (max), mean (μ) and standard deviation (σ) have been compared for the two models in the Table 3.

Table 3. The statistical values of Rotor Torque (kN-m)

	EC1			EC2		
Parameters	***σ***	***μ***	max	***σ***	***μ***	max
NTM	39.5	1012.1	1116.0	189.6	2962.0	3451.0
ETM	125.6	1225.2	1553.0	458.9	3011.6	4498.0
Percentage increase (%)	218.2	21.1	39.2	142.0	1.7	30.3
	EC3			EC4		
Parameters	***σ***	***μ***	max	***σ***	***μ***	max
NTM	125.5	4181.8	4533.0	225.9	4222.7	5066.0
ETM	223.0	4188.7	4831.0	340.3	4229.3	5224.0
Percentage increase (%)	77.7	0.2	6.6	50.6	0.2	3.1

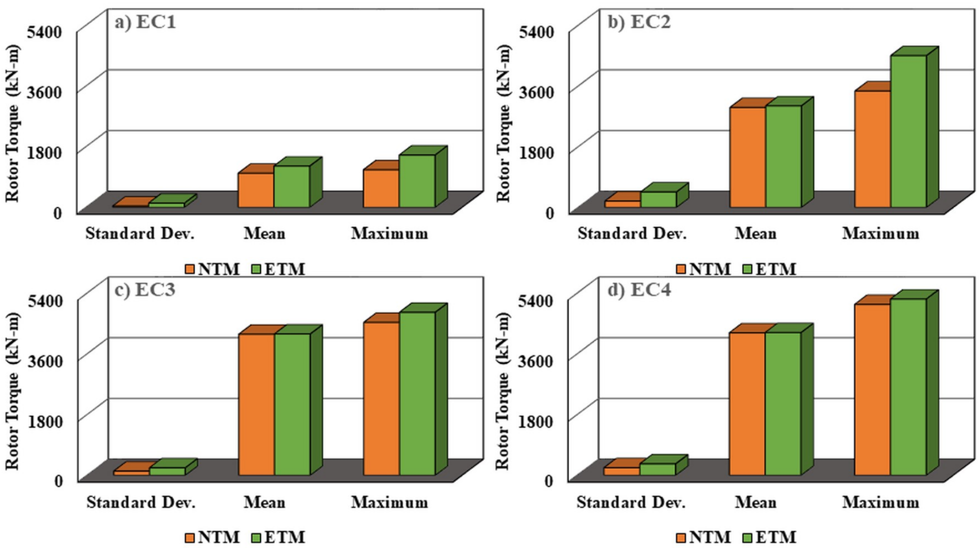

Fig. 7. Parametric comparison of rotor torque

The standard deviation shows increasing amplitude of fluctuation in extreme turbulence compared to the normal turbulence well. According to Table 3 and Fig. 7, the ETM has a greater standard deviation about 218 percent. Thus, this indicates that the dynamic analysis must be conducted to investigate the effect of turbulence, because the static analysis does not see these changes in the amplitude of fluctuation and calculates the mean of results almost identical in both models.

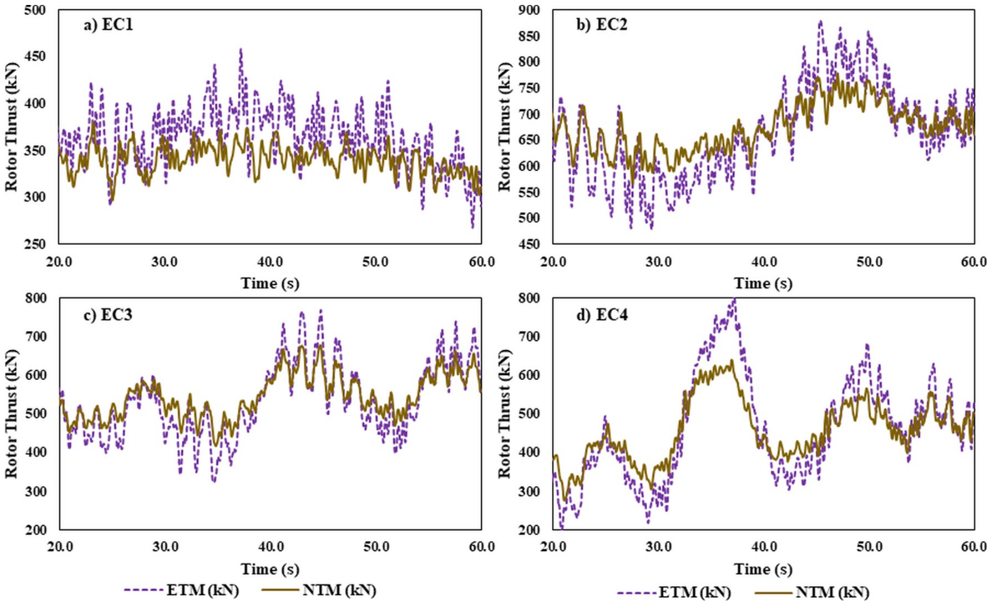

Fig. 8. The time history of the rotor thrust

The Diagram of Fig. 8 shows that the more turbulence the model, the thrust force exerted on the turbine is reduced. However, the fluctuations of this force during the time in ETM is still more than NTM.

Table 4. The statistical values of Rotor Thrust (kN)

	EC1			EC2		
Parameters	σ	μ	max	σ	μ	max
NTM	14.8	340.1	380.0	45.0	673.3	777.7
ETM	30.7	363.7	458.6	89.1	664.6	880.5
Percentage increase (%)	107.5	6.9	20.7	97.9	-1.3	13.2
	EC3			EC4		
Parameters	σ	μ	max	σ	μ	max
NTM	56.6	546.2	678.7	79.6	457.2	640.1
ETM	93.9	531.6	768.9	135.8	461.4	812.3
Percentage increase (%)	65.9	-2.7	13.3	70.6	0.9	26.9

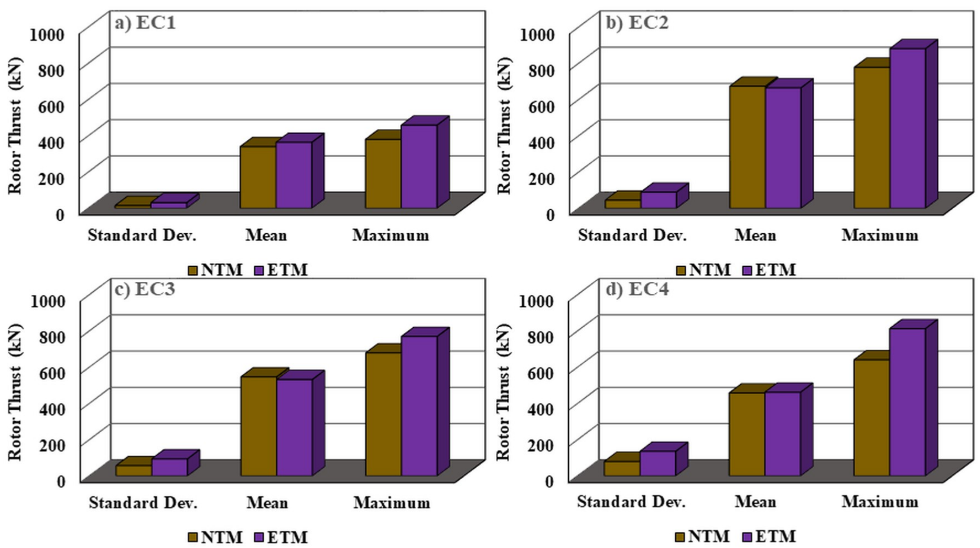

Fig. 9. Parametric comparison of rotor thrust

The negative values of the percent increase in Table 4 indicate that the mean and the maximum thrust forces generated by the turbine are reduced by increasing wind turbulence.

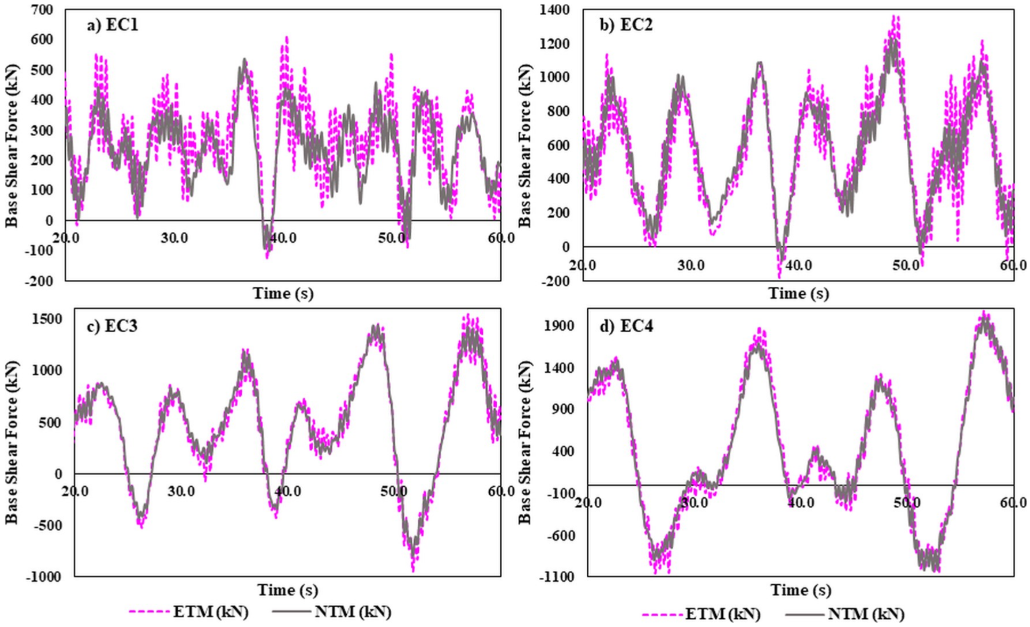

Fig. 10. The time history of base shear force

Table 5. The statistical values of Base Shear Force (kN)

	EC1			EC2		
Parameters	σ	μ	max	σ	μ	max
NTM	117.9	239.1	538.1	299.5	571.1	1234.0
ETM	133.8	262.1	613.9	325.3	562.3	1363.0
Percentage increase (%)	13.5	9.6	14.1	8.6	-1.6	10.5
	EC3			EC4		
Parameters	σ	μ	max	σ	μ	max
NTM	56.6	546.2	678.7	79.6	457.2	640.1
ETM	93.9	531.6	768.9	135.8	461.4	812.3
Percentage increase (%)	65.9	-2.7	13.3	70.6	0.9	26.9

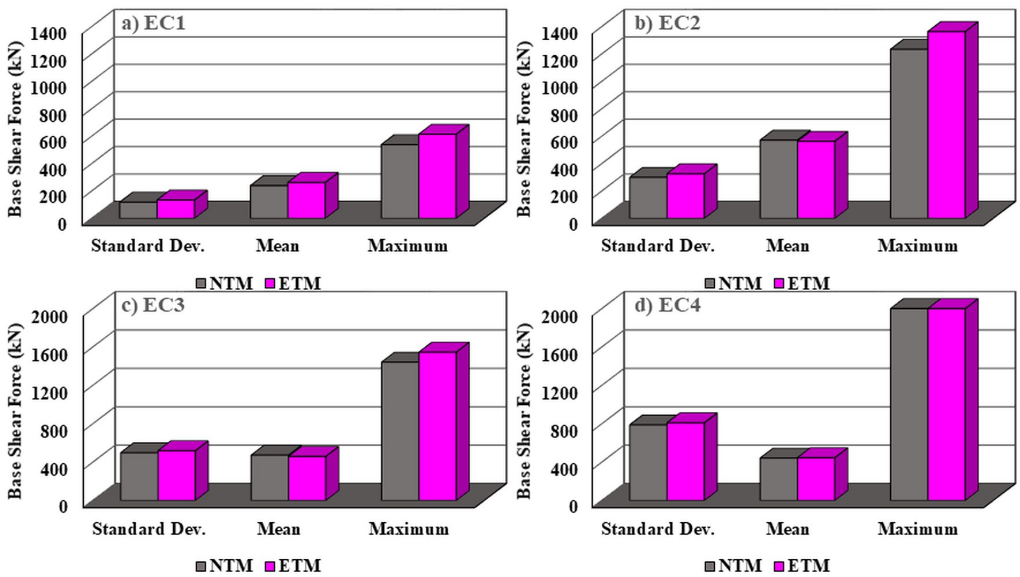

Fig. 11. Parametric comparison of base shear force

The Fig. 11 and Table 5 show that increasing wind turbulence leads to increasing the values of base shear structures and the fluctuations of this force.

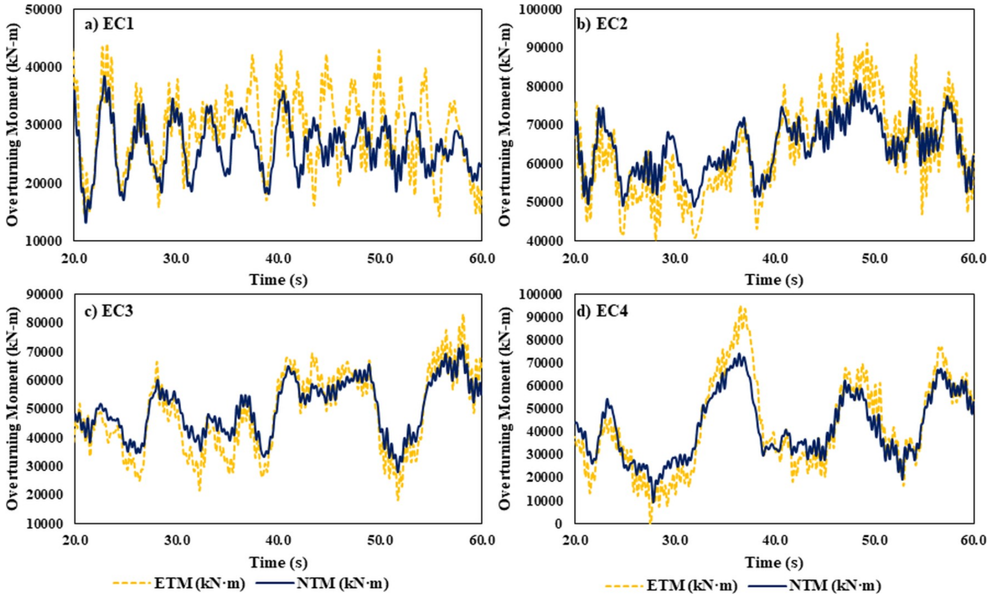

Fig. 12. The time history of overturning moment

Table 6. The statistical values of Overturning Moment (kN-m)

	EC1			EC2		
Parameters	***σ***	***μ***	max	***σ***	***μ***	max
NTM	4526.9	26311.9	38460.0	7166.4	64291.0	81510.0
ETM	6445.3	28922.6	44010.0	11701.9	63708.2	93780.0
Percentage increase (%)	42.4	9.9	14.4	63.3	-0.9	15.1
	EC3			EC4		
Parameters	***σ***	***μ***	max	***σ***	***μ***	max
NTM	9518.6	50187.2	72440.0	14409.0	42013.6	74360.0
ETM	13699.3	48160.1	83130.0	20166.3	42404.0	95330.0
Percentage increase (%)	43.9	-4.0	14.8	40.0	0.9	28.2

According to the Fig. 12 and 13 and Table 6, the overturning moment in the ETM has greater maximum values and amplitude of fluctuation than the NTM, but the mean response of the structure is almost close to each other in both models. Also according to the diagram, it becomes clear that the results of two models become closer to each other by increasing the time.

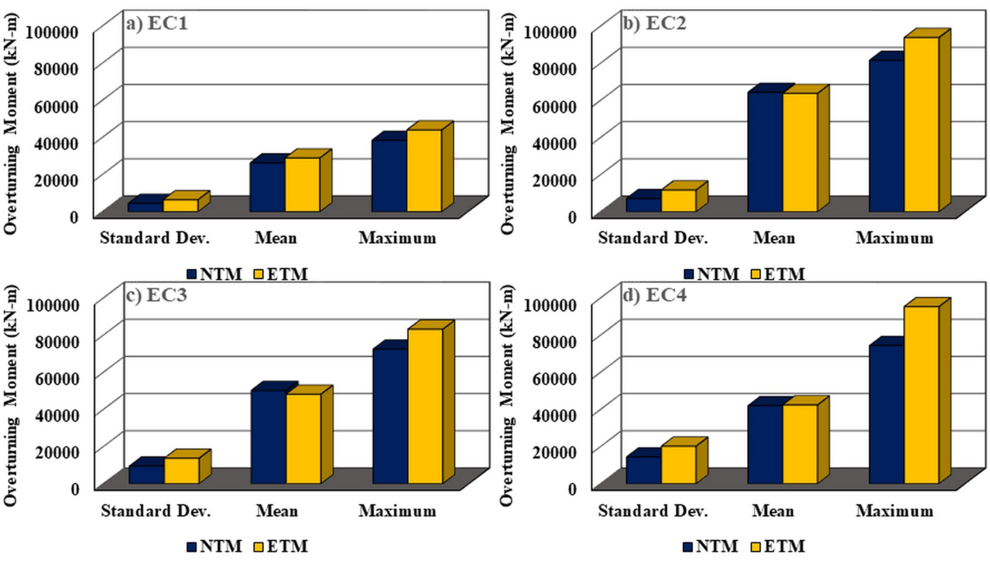

Fig. 13. Parametric comparison of overturning moment

6. Conclusion

This study dealt with the investigation of the effect for wind turbulence on the behavior of offshore wind turbine. For this purpose, the offshore wind turbine was under two models, namely the ETM and the NTM, of wind. After modeling and applying interaction conditions of water and structures, the equations governing the theory of BEM, the response of turbine (thrust force and rotor torque) and its holder structures (base shear force and turning moment) were compared in both turbulence models. The results of these comparisons show that in general, the amplitude of fluctuation amount of the response of turbine and its holder structures are increased by increasing wind turbulence, and considering the effect of this issue shows the necessity for dynamic analysis of offshore wind turbine. Because the static analysis is not able to measure the fluctuations and its effect on structures and shows only the mean values. Also the results showed that since the turbulence model does not change the mean wind speed, as shown in the diagrams the mean values in turbine response based on simulations using these two turbulence model are close to each other given the condition of each wind case.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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Nomenclature

F_D	Drag force (N)	c	Airfoil chord (m)
F_I	Inertia force (N)	v	Water velocity (m/s)
ρ_w	Water density (kg/m^3)	$\dot{v}$	Wave acceleration (m/s^2)
ρ_{air}	Air density (kg/m^3)	$\dot{u}$	Velocity of structure (m/s)
C_D	Drag coefficient	$\ddot{u}$	Acceleration of structure (m/s$^{2)}$
C_M	Inertia coefficient	V_{rel}	sum of the wind velocity and rotational speed (m/s)
C_L	Lift coefficient		

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Appendix A

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------- FAST INPUT FILE ------------------------------------------------------
NREL 5.0 MW Baseline Wind Turbine for Use in Offshore Analysis.
Properties from Dutch Offshore Wind Energy Converter (DOWEC) 6MW Pre-Design (10046_009.pdf) and REpower 5M 5MW (5m_uk.pdf); Compatible with FAST v7.02.
---------------------- SIMULATION CONTROL --------------------------------------
False      Echo          - Echo input data to "echo.out" (flag)
3          ADAMSPrep     - ADAMS preprocessor mode {1: Run FAST, 2: use FAST as a preprocessor to create an ADAMS model, 3: do both} (switch)
1          AnalMode      - Analysis mode {1: Run a time-marching simulation, 2: create a periodic linearized model} (switch)
3          NumBl         - Number of blades (-)
1024.0     TMax          - Total run time (s)
0.01       DT            - Integration time step (s)
---------------------- TURBINE CONTROL -------------------------------------------
0          YCMode        - Yaw control mode {0: none, 1: user-defined from routine UserYawCont, 2: user-defined from Simulink/Labview} (switch)
9999.9     TYCOn         - Time to enable active yaw control (s) [unused when YCMode=0]
1          PCMode        - Pitch control mode {0: none, 1: user-defined from routine PitchCntrl, 2: user-defined from Simulink/Labview} (switch)
0.0        TPCOn         - Time to enable active pitch control (s) [unused when PCMode=0]
2          VSContrl      - Variable-speed control mode {0: none, 1: simple VS, 2: user-defined from routine UserVSCont, 3: user-defined from Simulink/Labview} (switch)
9999.9     VS_RtGnSp     - Rated generator speed for simple variable-speed generator control (HSS side) (rpm) [used only when VSContrl=1]
9999.9     VS_RtTq       - Rated generator torque/constant generator torque in Region 3 for simple variable-speed generator control (HSS side) (N-m) [used only when VSContrl=1]
9999.9     VS_Rgn2K      - Generator torque constant in Region 2 for simple variable-speed generator control (HSS side) (N-m/rpm^2) [used only when VSContrl=1]
9999.9     VS_SlPc       - Rated generator slip percentage in Region 2 1/2 for simple variable-speed generator control (%) [used only when VSContrl=1]
2          GenModel      - Generator model {1: simple, 2: Thevenin, 3: user-defined from routine UserGen} (switch) [used only when VSContrl=0]
True       GenTiStr      - Method to start the generator {T: timed using TimGenOn, F: generator speed using SpdGenOn} (flag)
True       GenTiStp      - Method to stop the generator {T: timed using TimGenOf, F: when generator power = 0} (flag)
9999.9     SpdGenOn      - Generator speed to turn on the generator for a startup (HSS speed) (rpm) [used only when GenTiStr=False]
0.0        TimGenOn      - Time to turn on the generator for a startup (s) [used only when GenTiStr=True]
9999.9     TimGenOf      - Time to turn off the generator (s) [used only when GenTiStp=True]
1          HSSBrMode     - HSS brake model {1: simple, 2: user-defined from routine UserHSSBr, 3: user-defined from Labview} (switch)
9999.9     THSSBrDp      - Time to initiate deployment of the HSS brake (s)
9999.9     TiDynBrk      - Time to initiate deployment of the dynamic generator brake [CURRENTLY IGNORED] (s)
9999.9     TTpBrDp(1)    - Time to initiate deployment of tip brake 1 (s)
9999.9     TTpBrDp(2)    - Time to initiate deployment of tip brake 2 (s)
9999.9     TTpBrDp(3)    - Time to initiate deployment of tip brake 3 (s) [unused for 2 blades]
9999.9     TBDepISp(1)   - Deployment-initiation speed for the tip brake on blade 1 (rpm)
9999.9     TBDepISp(2)   - Deployment-initiation speed for the tip brake on blade 2 (rpm)
9999.9     TBDepISp(3)   - Deployment-initiation speed for the tip brake on blade 3 (rpm) [unused for 2 blades]
9999.9     TYawManS      - Time to start override yaw maneuver and end standard yaw control (s)
9999.9     TYawManE      - Time at which override yaw maneuver reaches final yaw angle (s)
0.0        NacYawF       - Final yaw angle for override yaw maneuvers (degrees)
9999.9     TPitManS(1)   - Time to start override pitch maneuver for blade 1 and end standard pitch control (s)
9999.9     TPitManS(2)   - Time to start override pitch maneuver for blade 2 and end standard pitch control (s)
9999.9     TPitManS(3)   - Time to start override pitch maneuver for blade 3 and end standard pitch control (s) [unused for 2 blades]
9999.9     TPitManE(1)   - Time at which override pitch maneuver for blade 1 reaches final pitch (s)
9999.9     TPitManE(2)   - Time at which override pitch maneuver for blade 2 reaches final pitch (s)
9999.9     TPitManE(3)   - Time at which override pitch maneuver for blade 3 reaches final pitch (s) [unused for 2 blades]
0.0        BlPitch(1)    - Blade 1 initial pitch (degrees)
0.0        BlPitch(2)    - Blade 2 initial pitch (degrees)
0.0        BlPitch(3)    - Blade 3 initial pitch (degrees) [unused for 2 blades]
0.0        BlPitchF(1)   - Blade 1 final pitch for pitch maneuvers (degrees)
0.0        BlPitchF(2)   - Blade 2 final pitch for pitch maneuvers (degrees)
0.0        BlPitchF(3)   - Blade 3 final pitch for pitch maneuvers (degrees) [unused for 2 blades]
---------------------- ENVIRONMENTAL CONDITIONS --------------------------------
9.80665    Gravity       - Gravitational acceleration (m/s^2)
---------------------- FEATURE FLAGS -------------------------------------------
True       FlapDOF1      - First flapwise blade mode DOF (flag)
True       FlapDOF2      - Second flapwise blade mode DOF (flag)
True       EdgeDOF       - First edgewise blade mode DOF (flag)
False      TeetDOF       - Rotor-teeter DOF (flag) [unused for 3 blades]
True       DrTrDOF       - Drivetrain rotational-flexibility DOF (flag)
True       GenDOF        - Generator DOF (flag)
True       YawDOF        - Yaw DOF (flag)
True       TwFADOF1      - First fore-aft tower bending-mode DOF (flag)
True       TwFADOF2      - Second fore-aft tower bending-mode DOF (flag)
True       TwSSDOF1      - First side-to-side tower bending-mode DOF (flag)
True       TwSSDOF2      - Second side-to-side tower bending-mode DOF (flag)
True       CompAero      - Compute aerodynamic forces (flag)
False      CompNoise     - Compute aerodynamic noise (flag)
---------------------- INITIAL CONDITIONS --------------------------------------
0.0        OoPDefl       - Initial out-of-plane blade-tip displacement (meters)
0.0        IPDefl        - Initial in-plane blade-tip deflection (meters)
0.0        TeetDefl      - Initial or fixed teeter angle (degrees) [unused for 3 blades]
0.0        Azimuth       - Initial azimuth angle for blade 1 (degrees)
12.1       RotSpeed      - Initial or fixed rotor speed (rpm)
0.0        NacYaw        - Initial or fixed nacelle-yaw angle (degrees)
0.0        TTDspFA       - Initial fore-aft tower-top displacement (meters)
0.0        TTDspSS       - Initial side-to-side tower-top displacement (meters)
---------------------- TURBINE CONFIGURATION -----------------------------------
63.0       TipRad        - The distance from the rotor apex to the blade tip (meters)
1.5        HubRad        - The distance from the rotor apex to the blade root (meters)
1          PSpnElN       - Number of the innermost blade element which is still part of the pitchable portion of the blade for partial-span pitch control [1 to BldNodes] [CURRENTLY IGNORED]
0.0        UndSling      - Undersling length [distance from teeter pin to the rotor apex] (meters) [unused for 3 blades]
0.0        HubCM         - Distance from rotor apex to hub mass [positive downwind] (meters)
```

```
   -5.01910   OverHang      - Distance from yaw axis to rotor apex [3 blades] or teeter pin [2 blades] (meters)
    1.9       NacCMxn       - Downwind distance from the tower-top to the nacelle CM (meters)
    0.0       NacCMyn       - Lateral    distance from the tower-top to the nacelle CM (meters)
    1.75      NacCMzn       - Vertical distance from the tower-top to the nacelle CM (meters)
   87.6       TowerHt       - Height of tower above ground level [onshore] or MSL [offshore] (meters)
    1.96256   Twr2Shft      - Vertical distance from the tower-top to the rotor shaft (meters)
    0.0       TwrRBHt       - Tower rigid base height (meters)
   -5.0       ShftTilt      - Rotor shaft tilt angle (degrees)
    0.0       Delta3        - Delta-3 angle for teetering rotors (degrees) [unused for 3 blades]
   -2.5       PreCone(1)    - Blade 1 cone angle (degrees)
   -2.5       PreCone(2)    - Blade 2 cone angle (degrees)
   -2.5       PreCone(3)    - Blade 3 cone angle (degrees) [unused for 2 blades]
    0.0       AzimB1Up      - Azimuth value to use for I/O when blade 1 points up (degrees)
---------------------- MASS AND INERTIA ----------------------------------------
    0.0       YawBrMass     - Yaw bearing mass (kg)
  240.00E3    NacMass       - Nacelle mass (kg)
   56.78E3    HubMass       - Hub mass (kg)
    0.0       TipMass(1)    - Tip-brake mass, blade 1 (kg)
    0.0       TipMass(2)    - Tip-brake mass, blade 2 (kg)
    0.0       TipMass(3)    - Tip-brake mass, blade 3 (kg) [unused for 2 blades]
2607.89E3     NacYIner      - Nacelle inertia about yaw axis (kg m^2)
  534.116     GenIner       - Generator inertia about HSS (kg m^2)
  115.926E3   HubIner       - Hub inertia about rotor axis [3 blades] or teeter axis [2 blades] (kg m^2)
---------------------- DRIVETRAIN ----------------------------------------------
  100.0       GBoxEff       - Gearbox efficiency (%)
   94.4       GenEff        - Generator efficiency [ignored by the Thevenin and user-defined generator models] (%)
   97.0       GBRatio       - Gearbox ratio (-)
False         GBRevers      - Gearbox reversal {T: if rotor and generator rotate in opposite directions} (flag)
   28.1162E3 HSSBrTqF       - Fully deployed HSS-brake torque (N-m)
    0.6       HSSBrDT       - Time for HSS-brake to reach full deployment once initiated (sec) [used only when HSSBrMode=1]
"Dummy"       DynBrkFi      - File containing a mech-gen-torque vs HSS-speed curve for a dynamic brake [CURRENTLY IGNORED] (quoted string)
  867.637E6   DTTorSpr      - Drivetrain torsional spring (N-m/rad)
    6.215E6   DTTorDmp      - Drivetrain torsional damper (N-m/(rad/s))
---------------------- SIMPLE INDUCTION GENERATOR ------------------------------
9999.9        SIG_SlPc      - Rated generator slip percentage (%) [used only when VSContrl=0 and GenModel=1]
9999.9        SIG_SySp      - Synchronous (zero-torque) generator speed (rpm) [used only when VSContrl=0 and GenModel=1]
9999.9        SIG_RtTq      - Rated torque (N-m) [used only when VSContrl=0 and GenModel=1]
9999.9        SIG_PORt      - Pull-out ratio (Tpullout/Trated) (-) [used only when VSContrl=0 and GenModel=1]
---------------------- THEVENIN-EQUIVALENT INDUCTION GENERATOR -----------------
9999.9        TEC_Freq      - Line frequency [50 or 60] (Hz) [used only when VSContrl=0 and GenModel=2]
9998          TEC_NPol      - Number of poles [even integer > 0] (-) [used only when VSContrl=0 and GenModel=2]
9999.9        TEC_SRes      - Stator resistance (ohms) [used only when VSContrl=0 and GenModel=2]
9999.9        TEC_RRes      - Rotor resistance (ohms) [used only when VSContrl=0 and GenModel=2]
9999.9        TEC_VLL       - Line-to-line RMS voltage (volts) [used only when VSContrl=0 and GenModel=2]
9999.9        TEC_SLR       - Stator leakage reactance (ohms) [used only when VSContrl=0 and GenModel=2]
9999.9        TEC_RLR       - Rotor leakage reactance (ohms) [used only when VSContrl=0 and GenModel=2]
9999.9        TEC_MR        - Magnetizing reactance (ohms) [used only when VSContrl=0 and GenModel=2]
---------------------- PLATFORM ------------------------------------------------
    2         PtfmModel     - Platform model {0: none, 1: onshore, 2: fixed bottom offshore, 3: floating offshore} (switch)
"NRELOffshrBsline5MW_Platform_Monopile_RF.dat"    PtfmFile    - Name of file containing platform properties (quoted string) [unused when PtfmModel=0]
---------------------- TOWER ---------------------------------------------------
   99         TwrNodes      - Number of tower nodes used for analysis (-)
"NRELOffshrBsline5MW_Tower_Monopile_RF.dat"       TwrFile     - Name of file containing tower properties (quoted string)
---------------------- NACELLE-YAW ---------------------------------------------
9028.32E6     YawSpr        - Nacelle-yaw spring constant (N-m/rad)
   19.16E6    YawDamp       - Nacelle-yaw damping constant (N-m/(rad/s))
    0.0       YawNeut       - Neutral yaw position--yaw spring force is zero at this yaw (degrees)
---------------------- FURLING -------------------------------------------------
False         Furling       - Read in additional model properties for furling turbine (flag)
"Dummy"       FurlFile      - Name of file containing furling properties (quoted string) [unused when Furling=False]
---------------------- ROTOR-TEETER --------------------------------------------
    0         TeetMod       - Rotor-teeter spring/damper model {0: none, 1: standard, 2: user-defined from routine UserTeet} (switch) [unused for 3 blades]
    0.0       TeetDmpP      - Rotor-teeter damper position (degrees) [used only for 2 blades and when TeetMod=1]
    0.0       TeetDmp       - Rotor-teeter damping constant (N-m/(rad/s)) [used only for 2 blades and when TeetMod=1]
    0.0       TeetCDmp      - Rotor-teeter rate-independent Coulomb-damping moment (N-m) [used only for 2 blades and when TeetMod=1]
    0.0       TeetSStP      - Rotor-teeter soft-stop position (degrees) [used only for 2 blades and when TeetMod=1]
    0.0       TeetHStP      - Rotor-teeter hard-stop position (degrees) [used only for 2 blades and when TeetMod=1]
    0.0       TeetSSSp      - Rotor-teeter soft-stop linear-spring constant (N-m/rad) [used only for 2 blades and when TeetMod=1]
    0.0       TeetHSSp      - Rotor-teeter hard-stop linear-spring constant (N-m/rad) [used only for 2 blades and when TeetMod=1]
---------------------- TIP-BRAKE -----------------------------------------------
    0.0       TBDrConN      - Tip-brake drag constant during normal operation, Cd*Area (m^2)
    0.0       TBDrConD      - Tip-brake drag constant during fully-deployed operation, Cd*Area (m^2)
    0.0       TpBrDT        - Time for tip-brake to reach full deployment once released (sec)
---------------------- BLADE ---------------------------------------------------
"NRELOffshrBsline5MW_Blade.dat"        BldFile(1)   - Name of file containing properties for blade 1 (quoted string)
"NRELOffshrBsline5MW_Blade.dat"        BldFile(2)   - Name of file containing properties for blade 2 (quoted string)
"NRELOffshrBsline5MW_Blade.dat"        BldFile(3)   - Name of file containing properties for blade 3 (quoted string) [unused for 2 blades]
---------------------- AERODYN -------------------------------------------------
"NRELOffshrBsline5MW_AeroDyn.ipt"      ADFile       - Name of file containing AeroDyn input parameters (quoted string)
---------------------- NOISE ---------------------------------------------------
"Dummy"       NoiseFile     - Name of file containing aerodynamic noise input parameters (quoted string) [used only when CompNoise=True]
---------------------- ADAMS ---------------------------------------------------
"NRELOffshrBsline5MW_ADAMSSpecific.dat"   ADAMSFile   - Name of file containing ADAMS-specific input parameters (quoted string) [unused when ADAMSPrep=1]
---------------------- LINEARIZATION CONTROL -----------------------------------
"NRELOffshrBsline5MW_Linear.dat"       LinFile      - Name of file containing FAST linearization parameters (quoted string) [unused when AnalMode=1]
---------------------- OUTPUT --------------------------------------------------
True          SumPrint      - Print summary data to "<RootName>.fsm" (flag)
```

1 OutFileFmt - Format for tabular (time-marching) output file(s) (1: text file [<RootName>.out], 2: binary file [<RootName>.outb], 3: both) (switch)
True TabDelim - Use tab delimiters in text tabular output file? (flag)
"ES10.3E2" OutFmt - Format used for text tabular output (except time). Resulting field should be 10 characters. (quoted string) [not checked for validity!]
0.0 TStart - Time to begin tabular output (s)
50 DecFact - Decimation factor for tabular output {1: output every time step} (-)
1.0 SttsTime - Amount of time between screen status messages (sec)
-3.09528 NcIMUxn - Downwind distance from the tower-top to the nacelle IMU (meters)
0.0 NcIMUyn - Lateral distance from the tower-top to the nacelle IMU (meters)
2.23336 NcIMUzn - Vertical distance from the tower-top to the nacelle IMU (meters)
1.912 ShftGagL - Distance from rotor apex [3 blades] or teeter pin [2 blades] to shaft strain gages [positive for upwind rotors] (meters)
3 NTwGages - Number of tower nodes that have strain gages for output [0 to 9] (-)
10,19,28 TwrGagNd - List of tower nodes that have strain gages [1 to TwrNodes] (-) [unused if NTwGages=0]
3 NBlGages - Number of blade nodes that have strain gages for output [0 to 9] (-)
5,9,13 BldGagNd - List of blade nodes that have strain gages [1 to BldNodes] (-) [unused if NBlGages=0]
OutList - The next line(s) contains a list of output parameters. See OutList.txt for a listing of available output channels, (-)
"WindVxi , WindVyi , WindVzi" - Longitudinal, lateral, and vertical wind speeds
"WaveElev" - Wave elevation at the platform reference point
"GenPwr , GenTq" - Electrical generator power and torque
"OoPDefl1 , IPDefl1 , TwstDefl1" - Blade 1 out-of-plane and in-plane deflections and tip twist
"BldPitch1" - Blade 1 pitch angle
"Azimuth" - Blade 1 azimuth angle
"RotSpeed , GenSpeed" - Low-speed shaft and high-speed shaft speeds
"TTDspFA , TTDspSS , TTDspTwst" - Tower fore-aft and side-to-side displacements and top twist
"TeetDefl , TeetDefl" - Dummy placeholders for the unavailable fore-aft and side-to-side displacements of the tower base at the monopile attachement location
"PtfmTDxi , PtfmTDyi , PtfmRDxi , PtfmRDyi" - Fore-aft, side-to-side, roll, and pitch displacements of the monopile at the mudline
"TeetDefl , TeetDefl" - Dummy placeholders for the unavailable fore-aft and side-to-side displacements of the monopile at 7m below the mudline
"Spn2MLxb1, Spn2MLyb1" - Blade 1 local edgewise and flapwise bending moments at span station 2 (approx. 50% span)
"RootFxc1 , RootFyc1 , RootFzc1" - Out-of-plane shear, in-plane shear, and axial forces at the root of blade 1
"RootMxc1 , RootMyc1 , RootMzc1" - In-plane bending, out-of-plane bending, and pitching moments at the root of blade 1
"RotTorq , LSSGagMya, LSSGagMza" - Rotor torque and low-speed shaft 0- and 90-bending moments at the main bearing
"RotThrust
"YawBrFxp , YawBrFyp , YawBrFzp" - Fore-aft shear, side-to-side shear, and vertical forces at the top of the tower (not rotating with nacelle yaw)
"YawBrMxp , YawBrMyp , YawBrMzp" - Side-to-side bending, fore-aft bending, and yaw moments at the top of the tower (not rotating with nacelle yaw)
"TwHt3MLxt, TwHt3MLyt" - Local side-to-side and fore-aft bending moments at tower gage 3 (approx. tower base / monopile attachement location)
"TwHt2MLxt, TwHt2MLyt" - Local side-to-side and fore-aft bending moments at tower gage 2 (approx. MSL)
"TwHt1MLxt, TwHt1MLyt" - Local side-to-side and fore-aft bending moments at tower gage 1 (approx. halfway between MSL and mudline)
"TwrBsFxt , TwrBsFyt , TwrBsFzt" - Fore-aft shear, side-to-side shear, and vertical forces at the mudline
"TwrBsMxt , TwrBsMyt , TwrBsMzt" - Side-to-side bending, fore-aft bending, and yaw moments at the mudline
"TeetDefl , TeetDefl , TeetDefl , TeetDefl" - Dummy placeholders for the unavailable local fore-aft shear, side-to-side shear, side-to-side bending moment, and fore-aft bending moment of the monopile at 7m below the mudline
"PtfmSurge, PtfmSway , PtfmRoll , PtfmPitch" - Platform surge, sway, roll, and pitch displacements (for use in calculating in Crunch the tower-top displacements in the inertia frame)
"RotThrust"
END of FAST input file (the word "END" must appear in the first 3 columns of this last line).

Appendix B

TurbSim Input File. Valid for TurbSim v1.50; 17-May-2010; Example file that can be used with simulations for the NREL 5MW Baseline Turbine

---------Runtime Options-----------------------------------
511347 RandSeed1 - First random seed (-2147483648 to 2147483647)
RanLux RandSeed2 - Second random seed (-2147483648 to 2147483647) for intrinsic pRNG, or an alternative pRNG: "RanLux" or "RNSNLW"
True WrBHHTP - Output hub-height turbulence parameters in binary form? (Generates RootName.bin)
True WrFHHTP - Output hub-height turbulence parameters in formatted form? (Generates RootName.dat)
True WrADHH - Output hub-height time-series data in AeroDyn form? (Generates RootName.hh)
True WrADFF - Output full-field time-series data in TurbSim/AeroDyn form? (Generates RootName.bts)
True WrBLFF - Output full-field time-series data in BLADED/AeroDyn form? (Generates RootName.wnd)
True WrADTWR - Output tower time-series data? (Generates RootName.twr)
True WrFMTFF - Output full-field time-series data in formatted (readable) form? (Generates RootName.u, RootName.v, RootName.w)
True WrACT - Output coherent turbulence time steps in AeroDyn form? (Generates RootName.cts)
True Clockwise - Clockwise rotation looking downwind? (used only for full-field binary files - not necessary for AeroDyn)
0 ScaleIEC - Scale IEC turbulence models to exact target standard deviation? [0=no additional scaling; 1=use hub scale uniformly; 2=use individual scales]

--------Turbine/Model Specifications-----------------------
31 NumGrid_Z - Vertical grid-point matrix dimension
31 NumGrid_Y - Horizontal grid-point matrix dimension
0.5 TimeStep - Time step [seconds]
1024.0 AnalysisTime - Length of analysis time series [seconds]
1024.0 UsableTime - Usable length of output time series [seconds] (program will add GridWidth/MeanHHWS seconds)
90.0 HubHt - Hub height [m] (should be > 0.5*GridHeight)
145.0 GridHeight - Grid height [m]
145.0 GridWidth - Grid width [m] (should be >= 2*(RotorRadius+ShaftLength))

```
 0            VFlowAng        - Vertical mean flow (uptilt) angle [degrees]
 0            HFlowAng        - Horizontal mean flow (skew) angle [degrees]

--------Meteorological Boundary Conditions-------------------
IECKAI        TurbModel       - Turbulence model ("IECKAI"=Kaimal, "IECVKM"=von Karman, "GP_LLJ", "NWTCUP", "SMOOTH", "WF_UPW", "WF_07D", "WF_14D", or "NONE")
"1-ed3"       IECstandard     - Number of IEC 61400-x standard (x=1,2, or 3 with optional 61400-1 edition number (i.e. "1-Ed2") )
"B"           IECturbc        - IEC turbulence characteristic ("A", "B", "C" or the turbulence intensity in percent) ("KHTEST" option with NWTCUP, not used for other models)
NTM           IEC_WindType    - IEC turbulence type ("NTM"=normal, "xETM"=extreme turbulence, "xEWM1"=extreme 1-year wind, "xEWM50"=extreme 50-year wind, where x=wind turbine class 1, 2, or 3)
default       ETMc            - IEC Extreme turbulence model "c" parameter [m/s]
PL            WindProfileType - Wind profile type ("JET"=Low-level jet,"LOG"=Logarithmic,"PL"=Power law, or "default", or "USR"=User-defined)
 90.          RefHt           - Height of the reference wind speed [m]
 28.0         URef            - Mean (total) wind speed at the reference height [m/s]
default       ZJetMax         - Jet height [m] (used only for JET wind profile, valid 70-490 m)
default       PLExp           - Power law exponent [-] (or "default")
default       Z0              - Surface roughness length [m] (or "default")

--------Non-IEC Meteorological Boundary Conditions------------
default       Latitude        - Site latitude [degrees] (or "default")
0.05          RICH_NO         - Gradient Richardson number
default       UStar           - Friction or shear velocity [m/s] (or "default")
default       ZI              - Mixing layer depth [m] (or "default")
default       PC_UW           - Hub mean u'w' Reynolds stress [(m/s)^2] (or "default")
default       PC_UV           - Hub mean u'v' Reynolds stress [(m/s)^2] (or "default")
default       PC_VW           - Hub mean v'w' Reynolds stress [(m/s)^2] (or "default")
default       IncDec1         - u-component coherence parameters (e.g. "10.0   0.3e-3" in quotes) (or "default")
default       IncDec2         - v-component coherence parameters (e.g. "10.0   0.3e-3" in quotes) (or "default")
default       IncDec3         - w-component coherence parameters (e.g. "10.0   0.3e-3" in quotes) (or "default")
default       CohExp          - Coherence exponent (or "default")

--------Coherent Turbulence Scaling Parameters-------------------
"M:\coh_events\eventdata"   CTEventPath   -   Name of the path where event data files are located
"Random"      CTEventFile     - Type of event files ("random", "les" or "dns")
true          Randomize       - Randomize disturbance scale and location? (true/false)
 1.0          DistScl         - Disturbance scale (ratio of dataset height to rotor disk).
 0.5          CTLy            - Fractional location of tower centerline from right (looking downwind) to left side of the dataset.
 0.5          CTLz            - Fractional location of hub height from the bottom of the dataset.
10.0          CTStartTime     - Minimum start time for coherent structures in RootName.cts [seconds]

==================================================
```