DYNAMIC BEHAVIOR OF PARKED WIND TURBINE AT EXTREME WIND SPEED

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In wind turbine design process, a series of load analysis is generally performed to determine ultimate and fatigue loads under various design load cases (DLCs) which is specified in IEC 61400. These design load scenario covers not only normal operating condition but also startup, shutdown, parked and other scenario which is assumed to occur during the expected lifetime of wind turbine. This research focus on vibration problem under 50-year storm conditions while rotor is parked and blades are feathered. In this parked scenario, effect of a wind direction change of up to ± 180 degrees for both cases of standstill and idling is analyzed by time domain simulations using two different coupled aero-hydro-servo-elastic codes. Trend in modern wind turbines is development of bigger, lighter and more flexible rotors where vibration issues may cause aero-elastic instabilities which have a serious impact on the ultimate loads. The DTU 10MW Reference Wind Turbine (RWT) is chosen as wind turbine model in this research.

Keyword: Wind turbine design[1], Aero-elastic simulation[2], Fluid-structure interaction [3]

1. BACKGROUND AND INTRODUCTION

Among Renewable energy source, especially offshore wind energy gains prominence because energy potential of offshore wind is abundant in Japan. Toward widespread use of offshore wind energy in Japan, accurate computation of coupled wind turbine structural dynamics, aerodynamics, hydrodynamics, mooring dynamics with control algorithms is highly significant for design optimization and certification process of offshore wind turbine. In the design process, all of design load cases (DLCs) which are prescribed in IEC61400-3$^{1)}$ have to be analyzed for load estimation in order to design the wind turbine components. In some wind turbine designs, the maximum ultimate load is expected for some components to occur under extreme wind speed condition in DLC6.x, even though wind turbine is parked with the rotor brake or idling to minimize loads. On top of that, effect of a wind direction change of up to ± 180° is investigated in DLC6.2, since loss of electrical power network at an early stage in a storm is assumed. Figure 1 shows an example yaw misalignment case of 90 degrees to realize the difficulty and challenge in this analysis. Above operating wind speed, wind turbine system is feathering the blades to avoid the unwanted aerodynamic load as it is assuming the rotor confronts wind direction. Besides, in this loss of the electrical power network case, extremely strong wind is coming to the parked rotor from lateral direction and position of each blades try to balance with large vibration due to the strong turbulent inflow and their deflection. As angle of attack is around 90 degrees with large fluctuation due to the turbulent inflow and deflection of blade, the lift and drag coefficient of airfoil data in this angle of attack region are associated with high uncertainties and generally unavailable. Furthermore as the flow is largely separated from whole blade, special care for the wake is also needed. Systematic approach is also required for wind turbine designer to solve this issue.

In this research, authors investigated vibration problem of parked land-based wind turbine by using the DTU 10MW RWT$^{2)}$ under extreme wind speed. Time domain simulation is carried out by coupled structural, hydrodynamic, control and aerodynamic analysis codes HAWC2$^{3)}$ and FAST$^{4), 5)}$. HAWC2 is developed by the Technical University of Denmark and FAST is developed by National Renewable Energy Laboratory.

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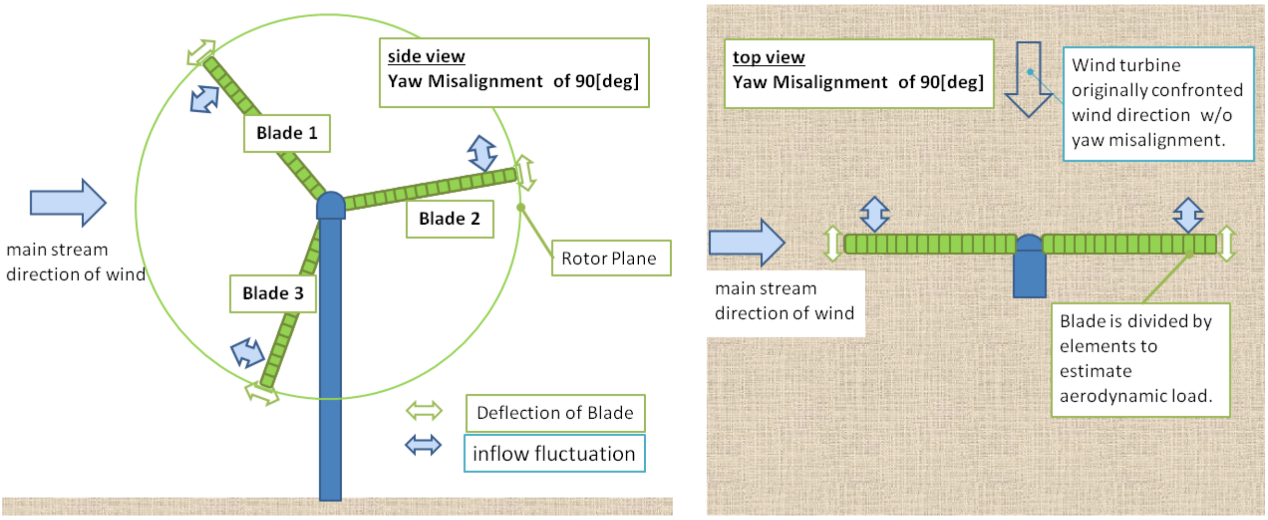


Figure 1:Schematics of a yaw misalignment case of 90 degree

2. DTU 10MW RWT MODEL

In terms of the trend of modern wind turbines, DTU 10MW RWT model (Figure2) is used in this research. Though the biggest size of wind turbine is 8MW for the time being, modern wind turbine is growing its capacity and appearance of 10MW wind turbine is matter of time. DTU 10MW RWT model was designed for offshore site for an IEC class 1A wind climate and was in general a traditional three-bladed, upwind wind turbine by the Technical University of Denmark in the Light Rotor Project. As the focus in the Light Rotor project was the rotor design, the structural definition of DTU 10MW RWT except of the blades was obtained by upscaling the artificial NREL 5MW reference turbine[6)] by applying the classical similarity rules. An overall description of the wind turbine is seen in Table 1. Major change from NREL 5MW is as follows.

- The IEC class changed, because the DTU 10MW RWT is made for an offshore wind climate.
- The hub height is lower, because a shorter tower is possible offshore.
- The drivetrain concept changed from a high speed to a medium speed.
- The DTU 10MW blades have pre-bend to ensure tower clearance.

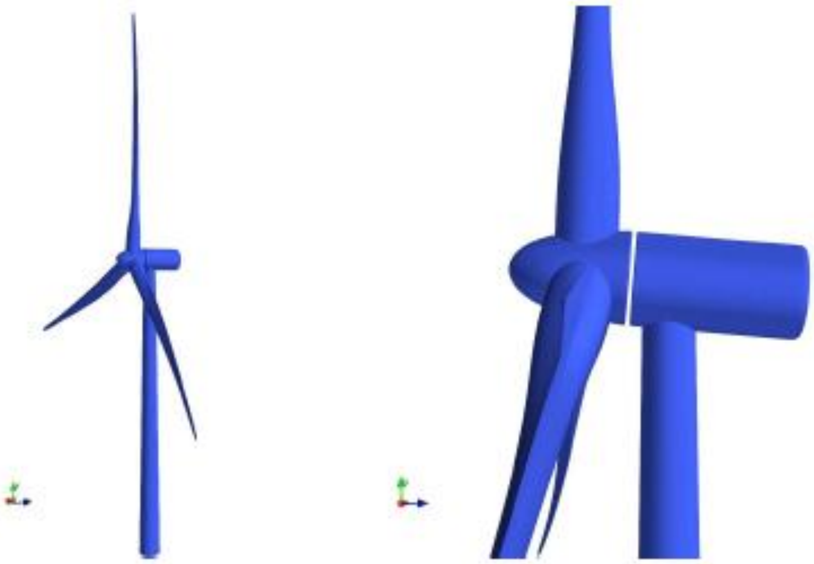


Figure 2: DTU 10 MW RWT MODEL[2)]

Table 1: Specification of DTU 10 MW Reference Wind Turbine[2)]

Description	Value
Raing	10MW
Rotor orientation, configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Drivetrain	Medium speed, Multiple stage gearbox
Rotor, Hub diameter	178.3m, 5.6m
Hub Height	119m
Cut-in, Rated, Cut-out wind speed	4m/s, 11.4m/s, 25m/s
Cut-in, Rated, Cut-out rotor speed	6RPM, 9.6RPM
Rated tip speed	90m/s
Overhang	7.07m, 5°, 2.5°
Pre bend	3m
Rotor mass	229ton(each blade mass ~41tons)
Nacelle mass	446tons
Tower mass	605tons

3. ANALYSIS CONDITION

To investigate vibration issue while wind turbine is parked with the rotor brake or idling, analysis condition of DLC6.2 was chosen and carried out. In DLC 6.2 extreme wind speed model (EWM) with full range of yaw misalignment shall be considered. Since a loss of the electrical power network at an early stage in a storm containing the extreme wind situation, shall be assumed. Unless power back-up is provided for the control and yaw system with a capacity for yaw alignment for a period of at least 6 h , the effect of a wind direction change of up to ± 180º shall be analyzed.

To analyze the cases for the full range of yaw misalignment, DLC6.2 by discrete yaw angles in increments of 30° (i.e., -150º, -120º, …, 180º) is considered in the simulations. Other analysis condition is summarized in Table 2. In this research, a land-based version of the wind turbine used in order to simplify the interpretation of analysis result, though DTU 10MW RWT model is designed for an offshore wind site.

We carried out DLC6.2 analysis by two state of art design analysis codes HAWC2 and FAST. We used the FAST v8.12 model which was provided by Borg. [7)] Regarding the difference between FAST model and HAWC2 model, no pre-bend and no torsional blade DOF in FAST and the turbulence model is different. HAWC2 model is a multi-body formulation based on a finite element implementation of Timoshenko beam theory, while FAST uses a mode shape formulation with limited DOF. However both models are consistent in terms of system identification as shown in Table 3. [7)]

Table 2: Summary of analysis condition

Description	Value
Wind Turbine Class (IEC)	Class 1
Wind Model	extreme wind speed model (EWM)
Turbulence Intensity (IEC)	11%
WSP, 50 year recurrence	50 [m/s]
Spectral Model	Kaimal
Yaw Misalignment	-150, -120, 90, …..,150, 180[deg]
Blade Pitch	Feather to 90 [deg]
Rotor	Idle or Standstill
vertical power-law wind-shear exponent	0.11
Simulation Time	3600[sec]
Random Seed	6 seeds

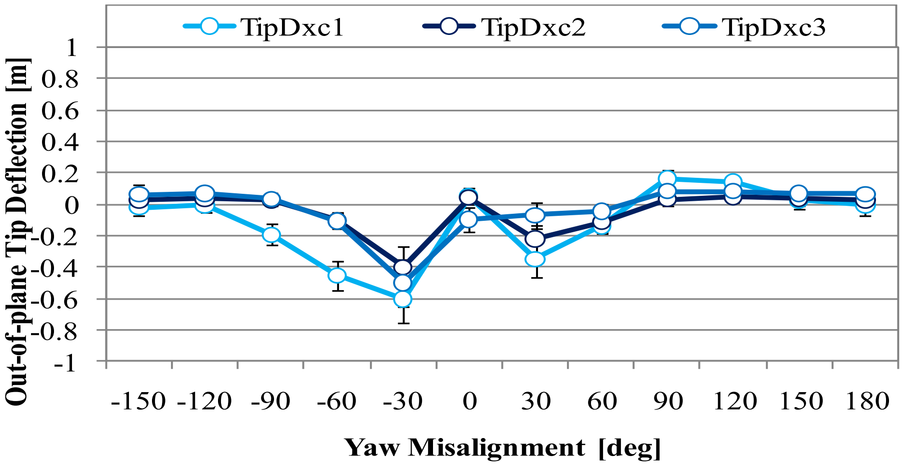
Table 3: Natural frequencies by FAST and HAWC2[7)]

Mode description	HAWC2 (Hz)	FAST (Hz)	Difference (%)
1st tower fore-aft and side-side mode	0.251	0.247	1.59
1st collective blade flap mode	0.63	0.636	0.95
1st asymmetric blade edge mode	0.935	0.975	4.28

4. ANALYSIS RESULTS

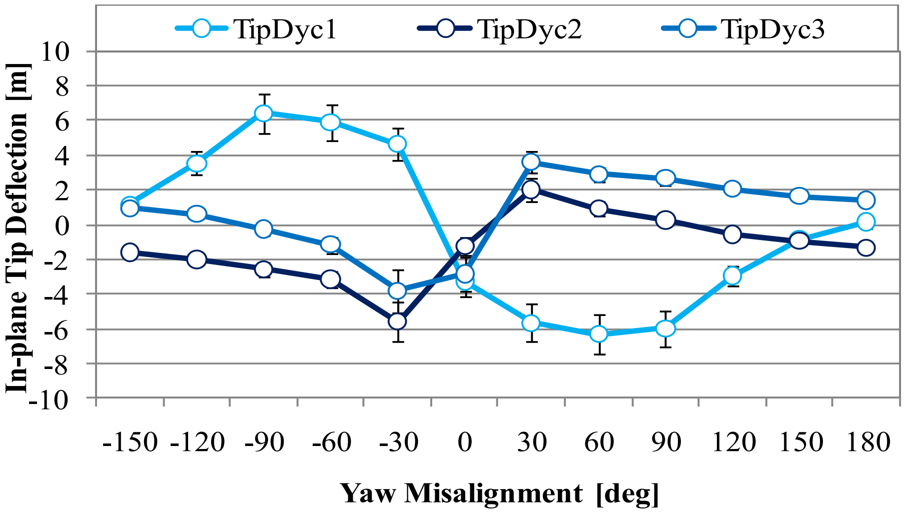
The full range of yaw misalignment results for 'Rotor-brake' and 'Rotor-free' by using the FAST model are summarized in Figure 3 and Figure 4, respectively. Mean value with plus/minus one standard deviation for the computation of 6 seeds about out-of-plane blade tip deflection, in-plane blade tip deflection, out-of-plane bending moment at blade root and in-plane bending moment at blade root are plotted. Apart from idling rotor speed difference, both results have similar magnitude and trend, though 'Rotor-brake' results show slightly larger magnitude of moment and Deflection to compare with 'Rotor-free' results. Fluctuation of blade tip deflection means the magnitude of vibration and has a similar trend with the moment fluctuation at blade root. The strong vibration occurs for cases with yaw misalignment of 30 and 60 degrees. Regarding the in-plane blade tip deflection and in-plane moment at blade root with yaw misalignment case of 30 and 60 degrees, the fluctuation range in 'Rotor-free' is interestingly spread over the value of each blades in 'Rotor-brake'. This is as if blades in 'Rotor-free' alternately changed their roles as one of the blades in 'Rotor-brake'.

The full range of yaw misalignment results for 'Rotor-free' by HAWC2 model are summarized in Figure5. Mean value with plus/minus one standard deviation for the computation of 6 seeds about out-of-plane bending moment at blade root, in-plane bending moment at blade root and Angle of attack at blade tip element are plotted. In HAWC2's 'Rotor-free' result, the large out-of-plane bending moment fluctuation is seen for yaw misalignment case of 30 degree. However this vibration isn't considered as the stall flutter[8)] in terms of the attack angle results in yaw misalignment case of 30 degree and -90degree. Figure 6 indicates the PSDs of bending moment at blade root and blade tip deflection for yaw misalignment of 30degree by HAWC2. Obtained PSDs of both bending moment at blade root and blade tip deflection show the significant peak around 0.8[Hz]. This peak is equivalent to the 9th edgewise blade mode by HAWC2 eigenanalysis result as shown in Table 4 and it could be solved by the redesign of edgewise stiffness distribution. Christian et al.[2)] also mentioned some combination of pitch sequence can solve the vibration issue. This outstanding peak around 0.8 [Hz] is not clear in other yaw misalignment cases. However FAST doesn't capture HAWC2 trend and it is presumably from that FAST has no prebend, no torsional blade DOF and the limited DOF based on mode shape.

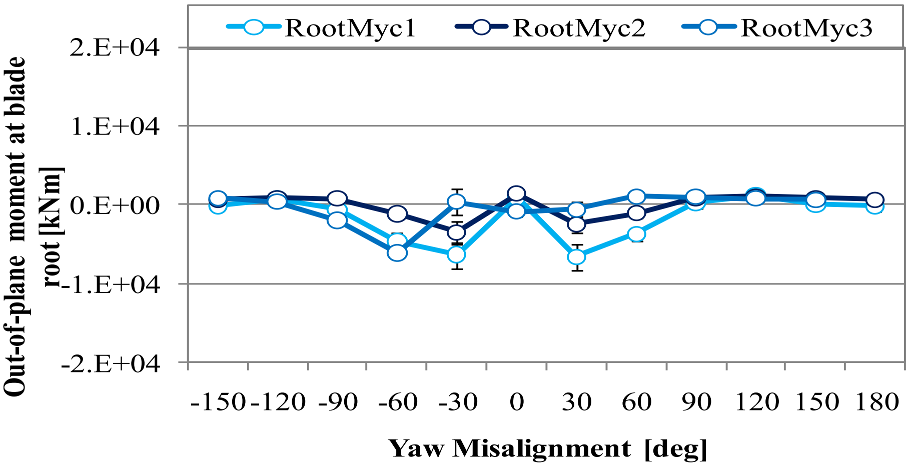


(a) Out-of-plane deflection at blade tip

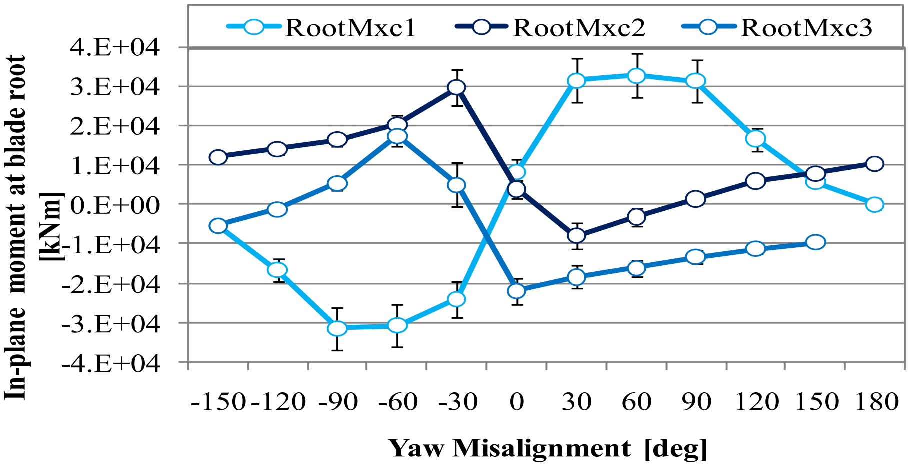
Figure 3:'Rotor-brake' simulation results by FAST



(b) In-plane deflection at blade tip

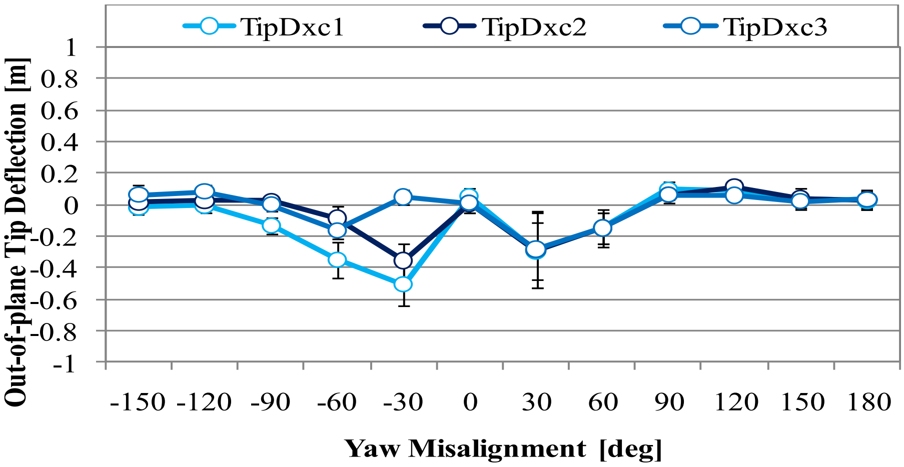


(c) Out-of-plane bending moment at blade root

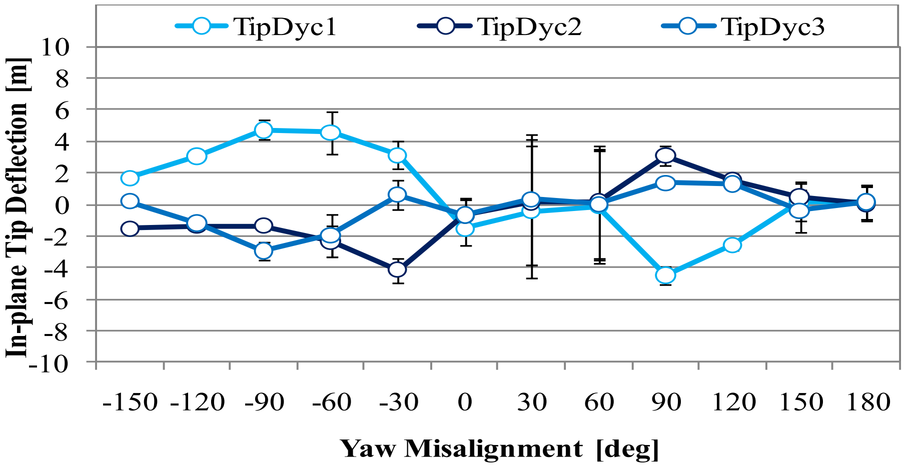


(d) In-plane bending moment at blade root

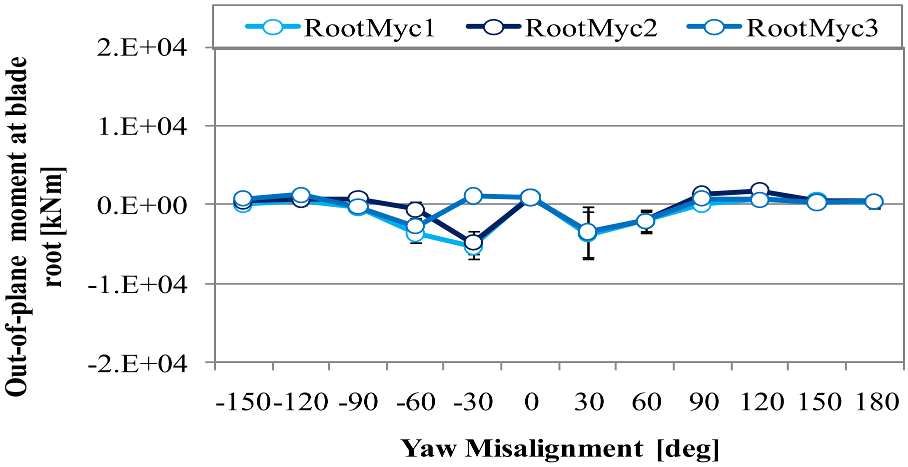
Figure 3:'Rotor-brake' simulation results by FAST(cont.)



(a) Out-of-plane deflection at blade tip

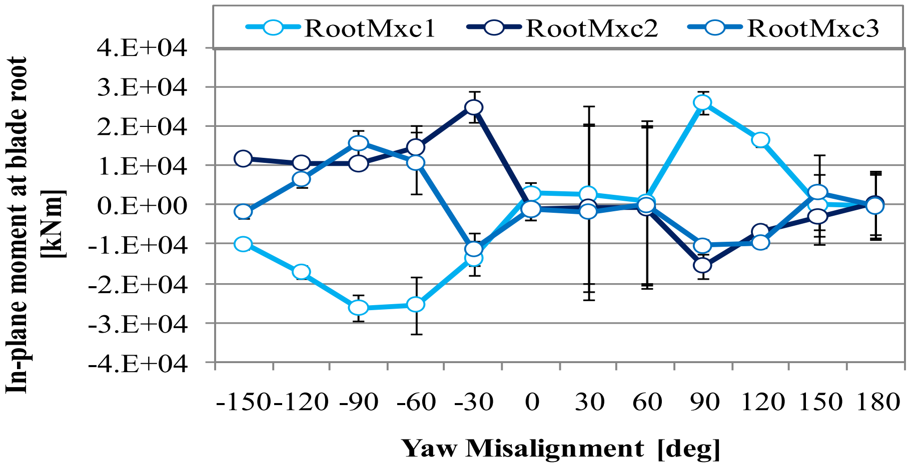


(b) In-plane deflection at blade tip



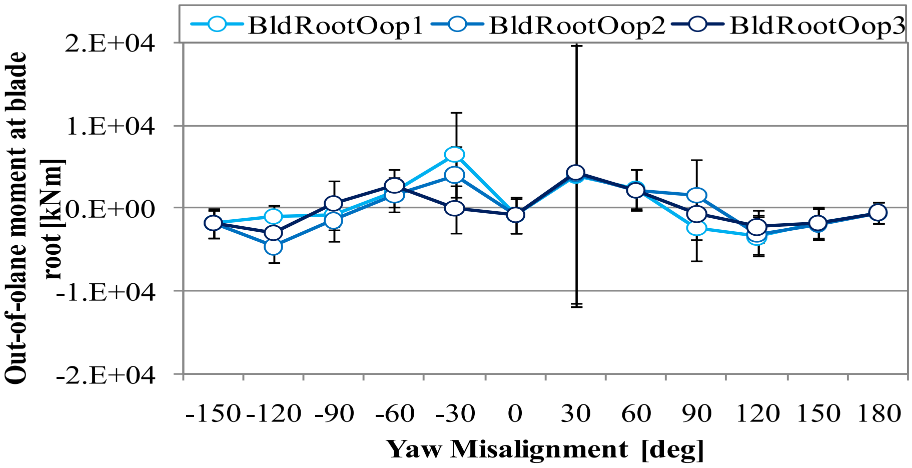
(c) Out-of-plane bending moment at blade root

Figure 4:'Rotor-free' simulation results by FAST

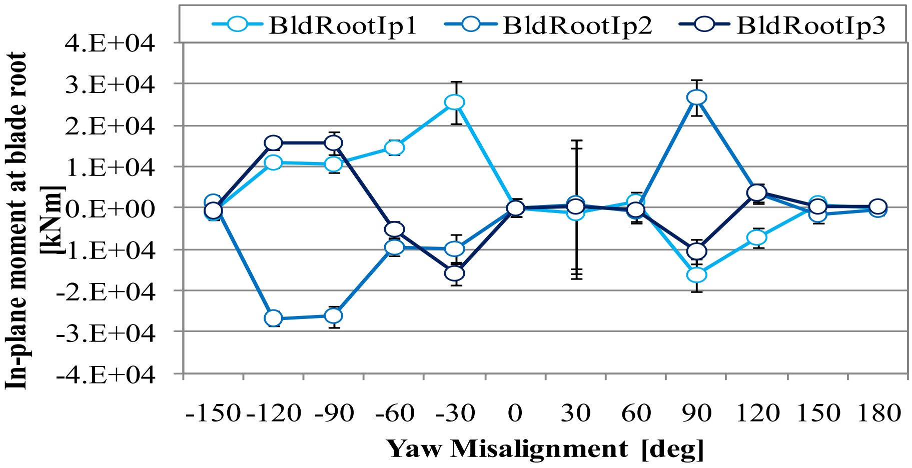


(d) In-plane bending moment at blade root

Figure 4:'Rotor-free' simulation results by FAST(cont.)

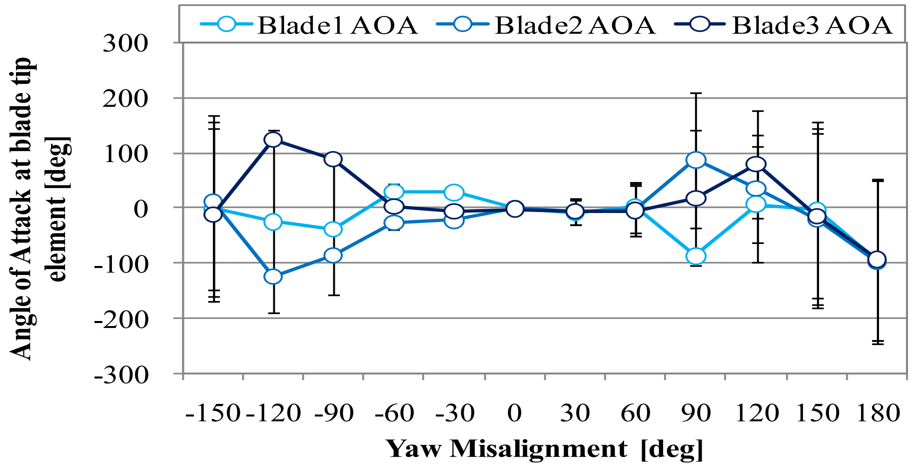


(a) Out-of-plane bending moment at blade root



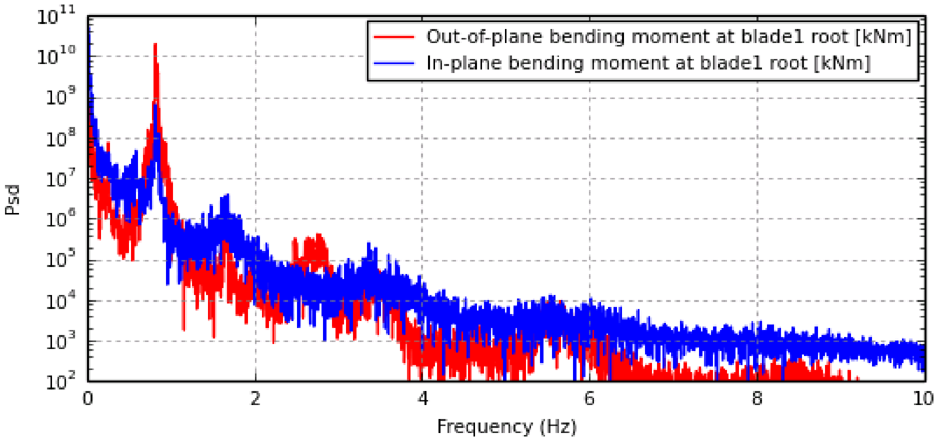
(b) In-plane bending moment at blade root

Figure 5:'Rotor-free' simulation results by HAWC2

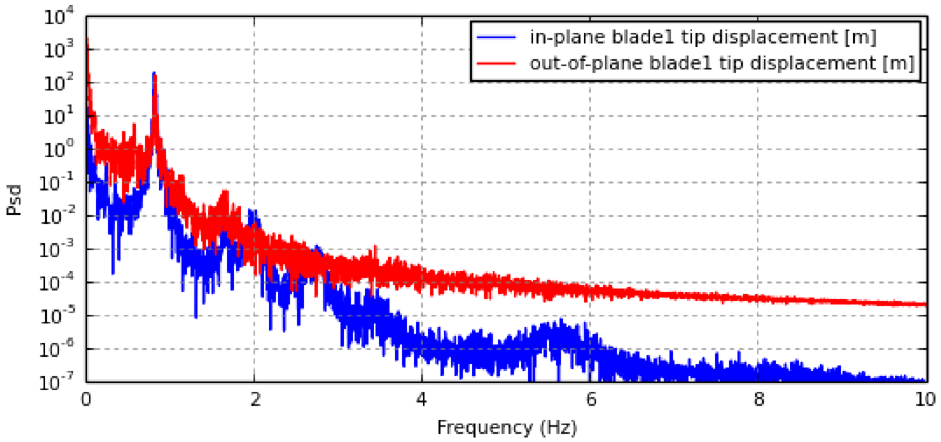


(c) Angle of attack at blade tip element

Figure 5:'Rotor-free' simulation results by HAWC2(cont.)

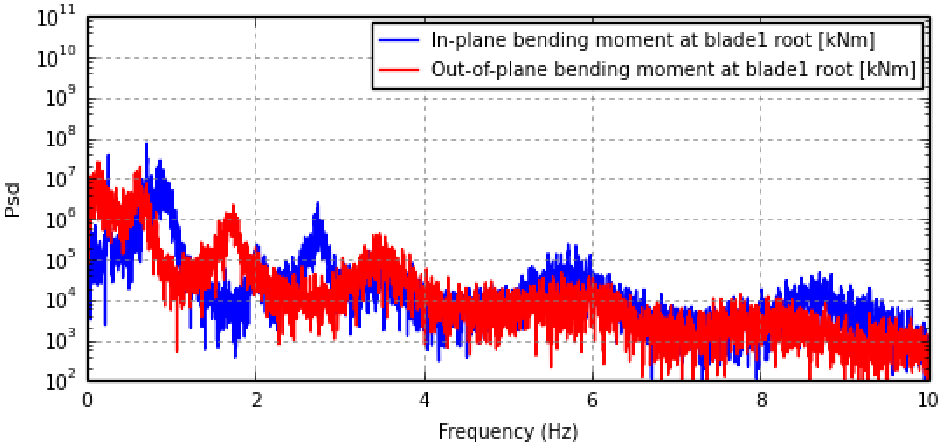


(a) PSD of bending moment at blade root for yaw misalignment of 30[deg]

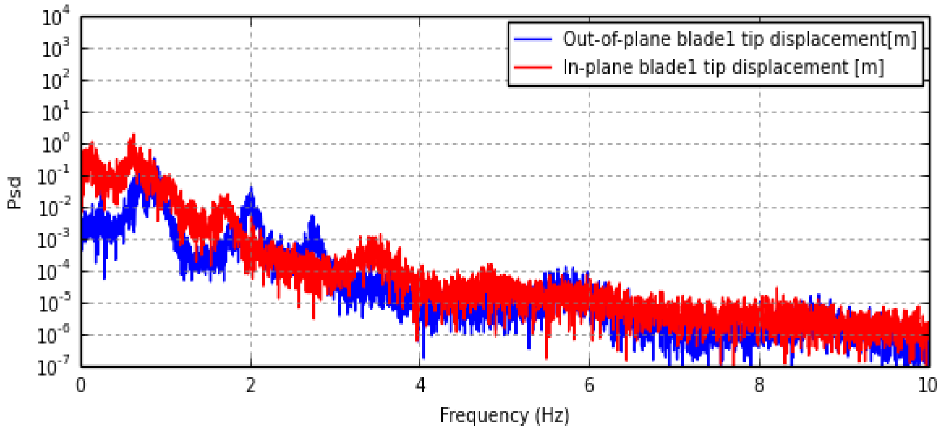


(b) PSD of blade tip Deflection for yaw misalignment of 30[deg]

Figure 6: PSDs of bending moment at blade root and blade tip deflection by HAWC2



(c) PSD of bending moment at blade root for yaw misalignment of -90[deg]



(d) PSD of blade tip Deflection for yaw misalignment of -90[deg]

Figure 6: PSDs of bending moment at blade root and blade tip deflection by HAWC2(cont.)

Table 4: Eigenanalysis results by HAWC2

	Modal Frequency [Hz]	
Mode	**Blade pitch angle of 0[deg]**	**Blade pitch angle of 90[deg]**
1	0.251	0.252
2	0.256	0.256
3	0.546	0.606
4	0.590	0.615
5	0.630	0.714
6	0.714	0.714
7	0.714	0.714
8	0.714	0.719
9	0.922	0.841
10	0.936	0.919

5. CONCLUSION

To investigate vibration issue while wind turbine is parked with the rotor brake or idling, analysis condition of DLC6.2 in IEC standard was chosen and carried out by the state of art design analysis codes HAWC2 and FAST. In FAST model results, fluctuation of blade tip deflection has a similar trend with the moment fluctuation at blade root. Obtained HAWC2 results show the serious vibration in bending moment at blade root under the specific yaw misalignment condition of 30degree. Authors assumed this vibration is the 9th edgewise blade mode by eigenanalysis in HAWC2 and it could be solved by the redesign of edgewise stiffness distribution. However FAST doesn't capture HAWC2 trend and it is presumably from that FAST has no prebend, no torsional blade DOF and the limited DOF based on mode shape. Though the several difficulties and challenges exist in this analysis, we have to know if wind turbine endures these extreme loads based on IEC's requirement. The further investigation about design load case of abnormal yaw misalignment is required to verify and support the current engineering tool which is used in the design process of wind turbine.

ACKNOWLEDGMENT

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