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Estimating wind and wave induced forces on a floating wind turbine

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Abstract:

In this work, the basic model for a spar buoy floating wind turbine, used by an extended Kalman filter, is presented and results concerning wind speed and wave force estimations are shown. The wind speed and aerodynamic forces are estimated using an extended Kalman filter based on a first-principles derived state space model of the floating wind turbine. The ability to estimate aero- and hydrodynamic states could prove crucial for the performance of model-based control methods applied on floating wind turbines.

Furthermore, two types of water kinematics, linear and non-linear, have been compared to investigate whether or not the low frequency content found in the non linear kinematics leads to increased loads.

Keywords: aerodynamics, hydrodynamics, state estimation, loads

1 Introduction

Several floating wind turbine concepts have been envisioned: a spar buoy, a tension leg platform and a barge platform among others. The novel concepts have necessitated the need for new control methods adapted to the special challenges posed by floating wind turbines. Among those challenges is the low frequency pitch of the floating structure.

In the literature investigations concerning control of the spar buoy concept concluded that detuning of the blade pitch controller gains gave stable closed-loop performance, as the closed-loop poles was below the tower pitch frequency [1, 2]. Model-based control of a floating wind turbine based on the barge platform concept has also been reported in literature [3], but the work assumes full state information. The assumption of full state information is however not realistic, as the turbulent wind field and waves, resulting in aerodynamic and hydrodynamic forces on the floating wind turbine, cannot easily be measured, necessitating a method of estimating such influences.

The floating wind turbine concept investigated in this work is the spar bouy concept inspired by the HyWind project [4].

A significant assumption in the modelling of ocean waves is the linearity of the wave kinematics. Though in deep waters where floating turbines are installed, linear kinematics may not be in gross error, the effect of the low frequency contributions of wave interactions is ignored in the linear assumption[5]. The usage of second order non-linear irregular waves along with wave crest kinematics allows a broader band of wave excitation to be investigated for floating structure design, especially the interaction of the wave-wave difference frequencies.

The first-principles model includes tower/platform degrees of freedom in both the fore-aft and the side-side directions. Numerical experiments in a high-fidelity aero-servo-hydro-elastic code are performed to assess the extended Kalman filters ability to estimate the hydrodynamic wave forces and the direction from which they come relative to the orientation of the wind turbine. The floating structure oscillations at different wave incident angles in the presence of second order non-linear waves are compared with the same motion when using linear kinematics.

Simulations are performed in the hydro-aero-servo elastic code HAWC2 [6]. The paper is structured in the following order: The water kinematic models are briefly discussed in Section 2. In Section 3 the extended Kalman and the wind turbine model it uses is presented. Finally, results are presented and discussed in Section 4 and conclusions are drawn in Section 5.

2 Water kinematics

In this work two water kinematic models are investigated in the high fidelity hydro-aero-servo-elastic software HAWC2: Irregular linear Airy waves with Wheeler stretching and second order irregular non-linear waves [7].

Significant wave height, H_s, of 4 6.4 and 8 m/s and time period of $T_P = 3.96\sqrt{Hs}$ for mean wind speeds of 6, 12 and 18 m/s, respectively. Fig. 1 depicts the power spectral density of the water surface elevation for the three different wind speeds for both the water kinematic models. Simulations are performed for a water depth of 320 m.

3 State estimation

An extended Kalman filter is used to estimate the internal states of the wind turbines as well as external disturbances such as wind and water fluctuations.

Ideally, the tower and floating spar buoy structures should modelled using e.g. Euler-Bernoulli or Timoshenko beam theory. However, as the hydrodynamic forces and the mooring lines affect the open loop modes and should accordingly be included in the modelling, increasing the modelling effort needed drastically, a more pragmatic approach has been used in this work. Fig. 2 shows the two tower modes used in the model. The first is the rigid body rotation of the entire floating structure, the second mode is the first elastic tower mode.

Transfer functions of the floating wind turbine have been obtained through numerous simulations in HAWC2 where the transfer function from blade pitch angle and generator torque to a number of outputs have been determined. Transfer functions from the control design model can then be compared those obtained in HAWC2 and the modal mass and stiffness of the floating tower modes can be fitted manually. The modal mass and stiffness is however closely coupled the mode shape, which has to be identified in the same process. Fig. 3 shows the Bode plots obtained from HAWC2 time simulations compared to the fitted models used by the extended Kalman filter. The tower modes are located at approx. 0.03 Hz 0.5 Hz and the tower mode shapes and modal masses can be fitted to match these modal frequencies.

The wind turbulence and water kinematics are modelled as second order dynamics systems in the control design model and have been fitted to the power spectral densities, of the wind speed at 45 m radius and water acceleration at 10 m depth, obtained from numerical simulations.

The extended Kalman filter [8] uses the sensors following sensors:

- Pitch angle of blade $i = 1, 2, 3$
- Electromagnetic torque generator torque
- Generator speed
- Tower top fore-aft acceleration
- Tower top side-side acceleration
- Flap-wise blade root bending moment at blade $i = 1, 2, 3$
- Edge-wise blade root bending moment at blade $i = 1, 2, 3$

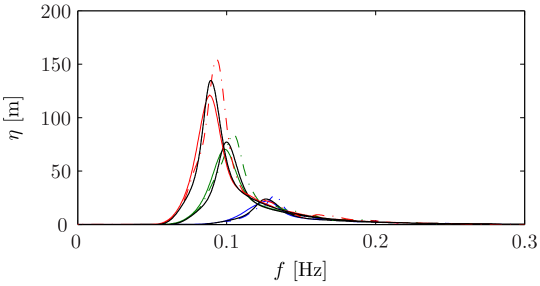

Figure 1: Power spectral density of water surface level for three different wind speeds 6 m/s, 12 m/s and 18 m/s plotted with blue, green and red lines, respectively. (-) Linear irregular Airy, (- -) Nonlinear narrow band. Solid black lines are ideal JONSWAP spectra for given parameters.

4 Results

In this section the results are presented. In Sec. 4.1 the loads are seen. In Sec. 4.2 the state estimations are seen.

4.1 Loads

Simulations are performed on the NREL 5MW reference wind turbine [2] with the spar bouy floating platform in the aero-servo-elastic code HAWC2 [6] using the benchmark PI-based controller proposed by Jonkman [2].

Simulations for three different mean speeds, 6 m/s, 12 m/s and 18 m/s, have been performed. For each mean wind speed four turbulence seeds have been used. Furthermore, the incoming wave direction have for a full 360 degrees study with 30 degrees increments have been performed. The turbulent wind field used in the simulations is presented

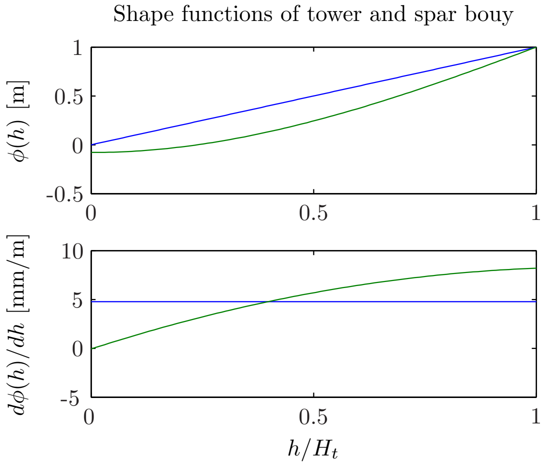

Figure 2: Mode shapes of tower and spar buoy. Blue line is the rigid body rotation of the tower and spar bouy. Green line is the first elastic tower mode.

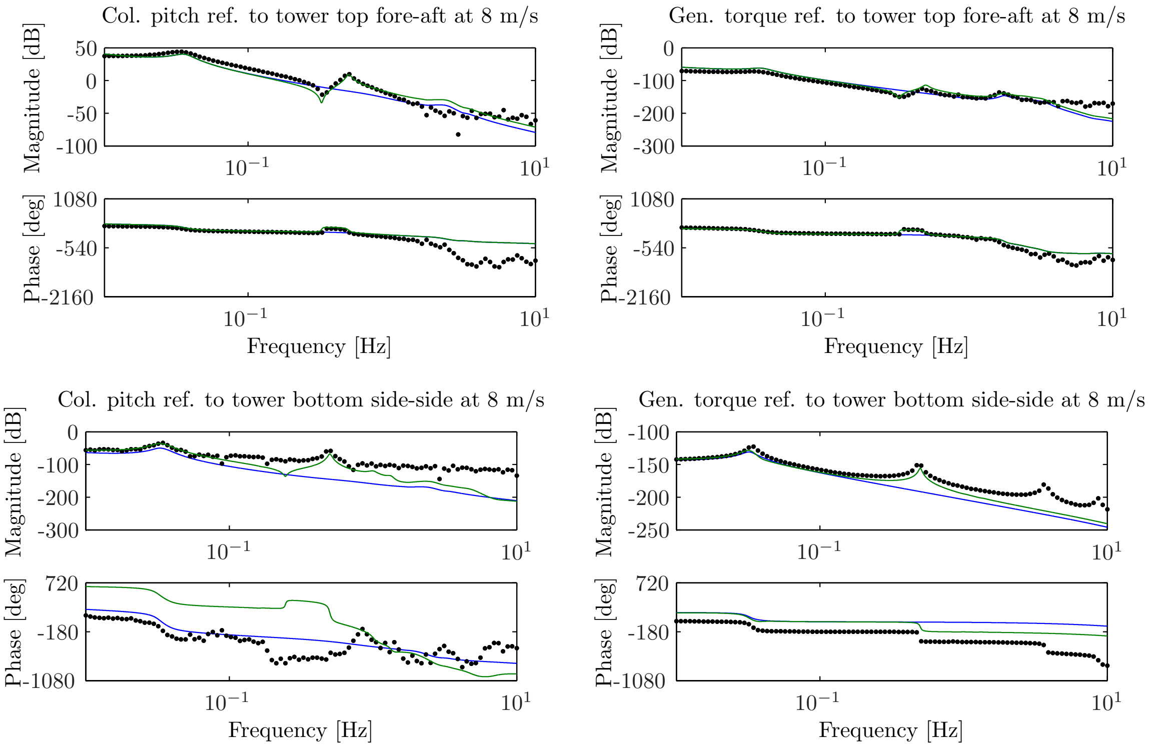

Figure 3: Transfer functions at a mean wind speed of 8 m/s. Black dots are obtained from HAWC2. Blue line is obtained from control design model including one tower mode only. Green line is obtained from control design model including two tower modes.

in Mann [9] with class A turbulence intensity as defined in [10], and a wind shear with a power coefficient of 0.2 is used together with a potential flow tower shadow model.

In Fig. 4 different performance metrics for the different wind speeds and wave directions are plotted for the different water kinematic models. It can be observed that no significant changes in loads occur for the different water kinematics. This could possibly be ascribed to the fact the linear irregular Airy waves use Wheeler stretching leading to higher loads, thus approaching the loads obtained with the non-linear water kinematics.

4.2 State estimation

Results for the extended Kalman filters ability to estimate the wind speed and water acceleration are seen Fig. 5 and Fig. 6. The results seen in the two figures are from simulations at 18 m/s with a single turbulence seed using the linear irregular Airy waves. Two extended Kalman filters are used: The first extended Kalman filter only includes the rigid body rotation mode of the tower in the control design model and the second extended Kalman filter also includes the first elastics mode of the tower in the control design model. It seen that when the extended Kalman filter does not include the first elastic mode in the control design model it will ascribe the frequency contribution of that mode, which is approx. 0.5 Hz, to the external disturbances, i.e. wind and water forces.

5 Conclusion

The presented method has demonstrated its ability to separate the influences of aero- and hydrodynamic, thus enabling better model-based control of wind turbines. Furthermore, the influence of linear versus nonlinear water kinematics and its influence on loads and the ability to separate estimations of aerodynamic and hydrodynamic forces affecting the floating wind turbine have been examined.

Acknowledgments

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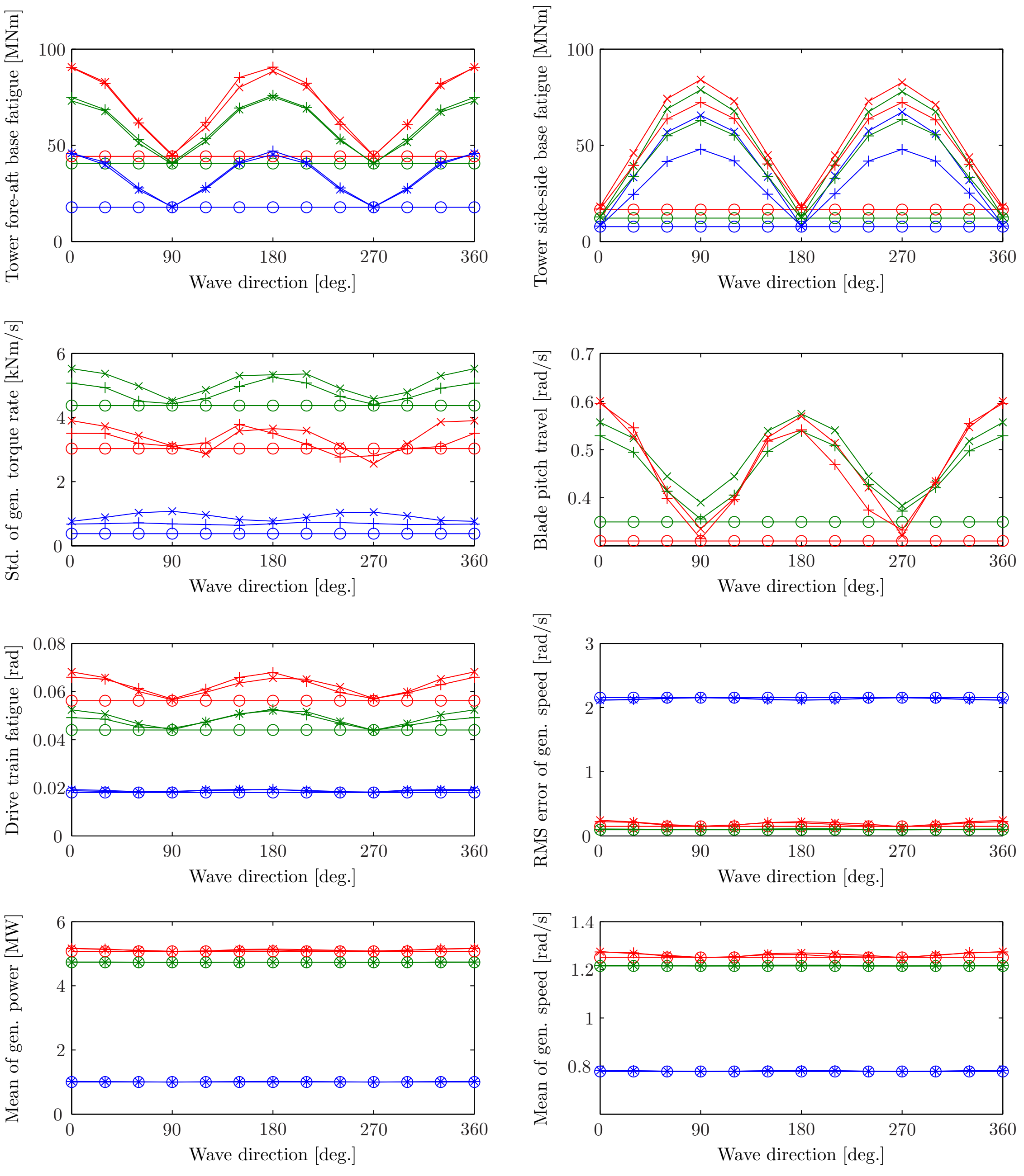

Figure 4: Performance metrics at different wave incidence angle for three different wind speeds 6 m/s, 12 m/s and 18 m/s plotted with blue, green and red lines, respectively.(o) No waves, (x) Linear irregular Airy with Wheeler stretching, (+) Non-linear.

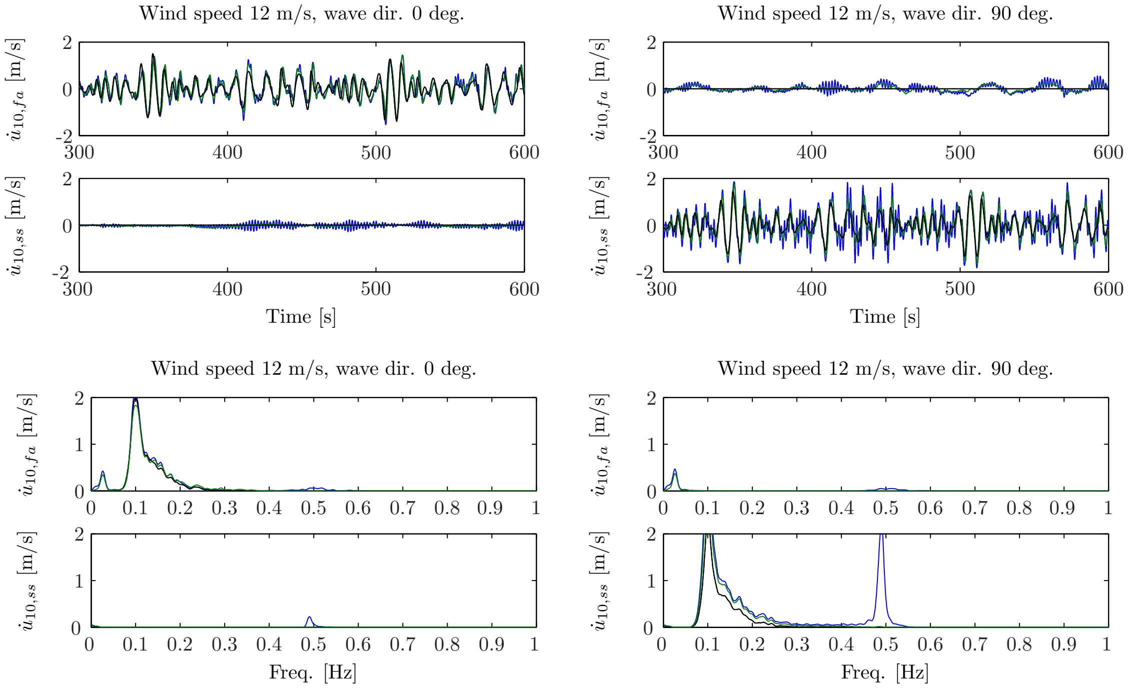

Figure 5: Estimation of hydrodynamic forces. Black line depicts the real water acceleration at 10 m depth. Blue and green lines depicts estimated hydrodynamic force by EKF based on models with one and two tower modes in each direction, respectively. Upper figures depicts time series and lower figures depicts power spectrum density.

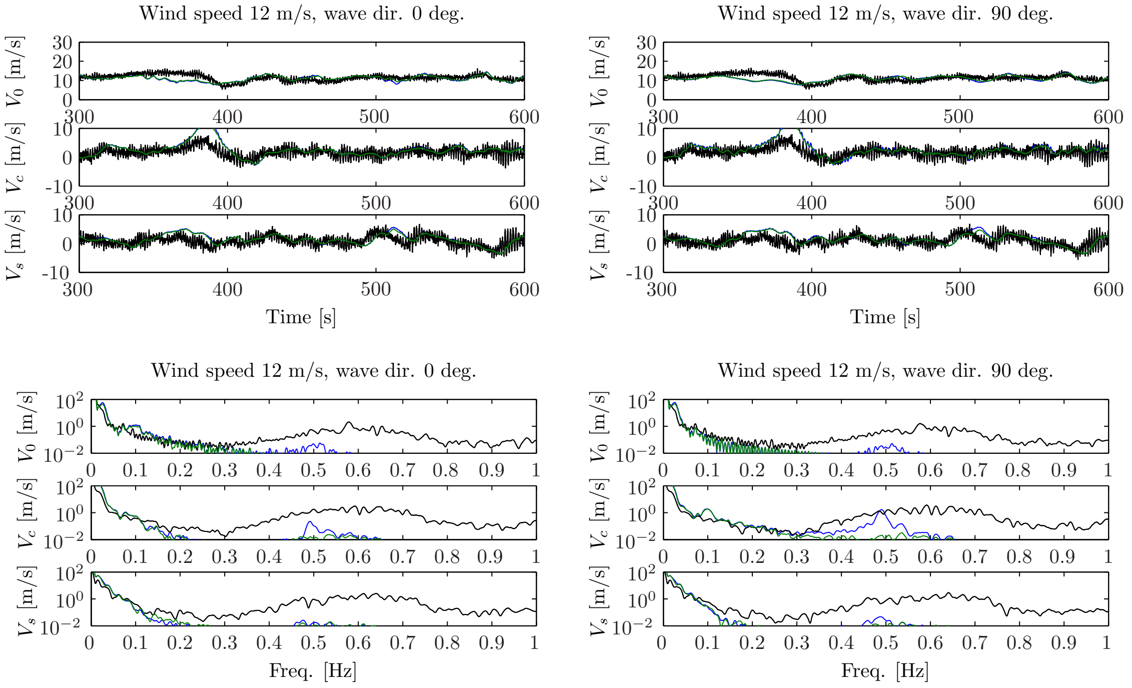

Figure 6: Estimation of wind speed in multi-blade coordinates. Black line depicts the real wind speed at 45 m radius of the blade. Blue and green lines depicts estimated wind speed by EKF based on models with one and two tower modes in each direction, respectively. Upper figures depicts time series and lower figures depicts power spectrum density.

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