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The TripleSpar Campaign: Implementation and Test of a Blade Pitch Controller on a Scaled Floating Wind Turbine Model

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Introduction

Experimental tests of floating wind turbines are usually done with Froude-scaling, which implies re-designing the blades for low Reynolds numbers. However, in the past tests as for full-scale turbines, blade-pitch control has not been included. Instead the rotor speed was kept constant through a servo motor. This poster presents a real-time blade pitch control system, with which the pitch control of the rotational speed for a low-Reynolds rotor at Froude-scaled frequencies was demonstrated.

Controller design

Figure 1 shows the principle concept of the gain-scheduled proportional-integral PI controller which is based on the NREL 5MW baseline controller.

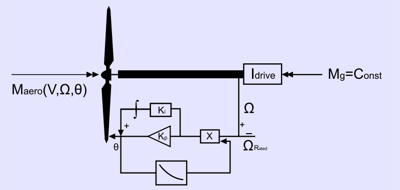

Figure 1: Blade-pitch control block diagram.

Very early the stability problem of floating wind turbines with a conventional on-shore pitch controller has been shown, which is caused by the aerodynamic damping $\frac{\delta F_a}{\delta V}$ in the 1DOF equation of pitch mode

$$\left(\frac{M_{55}+A_{55}}{L_T^2}\right)\ddot{x}_T+\left(\frac{B_{55}}{L_T^2}+\frac{\delta F_a}{\delta V}\right)\dot{x}_T+\frac{C_{55}}{L_T^2}x_T=F_{a,0}. \quad (1)$$

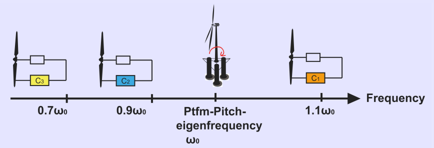

Figure 2: Controller with detuned gains.

One recommended solution is to keep the closed-loop (including control feedback) eigenfrequency of the drivetrain below the platform pitch mode to ensure stability. According to this theory, 3 different gain scheduling methodologies are implemented as Figure 2. here, C1 should show the most unstable behavior, whereas C3 should be stable.

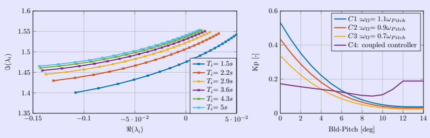

Figure 3: (a) Poles of pitch mode with $K_p = 0.1...0.4$ at wind speed 1.6[m/s]; (b) Gains of different controllers.

Another solution is discussed in [1], in which the closed-loop is considered with 5-DOFs. The simplified model is linearized at different wind speed so that the poles and zeros of the transfer function of the whole dynamic system can be plotted as Figure 3 (a) shows. By limiting the real part of the pole, the gains for each wind speed can be found (see Figure 3 (b)).

Simulation model

Figure 4 presents the test model, a 1:60 scaled DTU 10MW wind turbine, which is mounted on the INNWIND.EU TripleSpar. A simplified low-order simulation model is set up with only 3 rigid bodies: platform, tower, nacelle and a total of 5 DOFs: surge, heave, pitch, tower top displacement in downwind direction and the azimuth of the rotor. The 3 joints are marked with red color in the sketch. A fixed coordinate system with its origin on the sea water level and at the initial center of flotation is used to describe the platform's position and orientation.

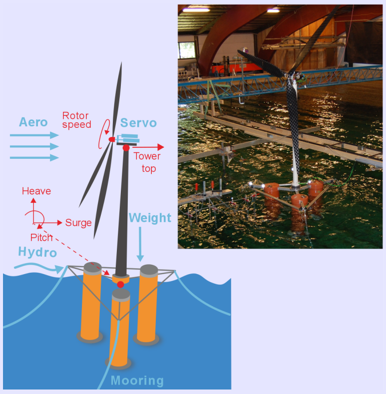

Figure 4: Configuration and coordinate system of the floating wind turbine.

BEM theory is used to create the aerodynamic model. First order hydrodynamic radiation and diffraction forces of the full-scale Triple-Spar are calculated with Ansys AQWA and then scaled into the model size according to the Froude similarity. The mooring dynamics are solved by using the quasi-static model.

Hardware implementation

Figure 5 shows the final hardware setup of the control loop, including two JVL MAC050 integrated servomotors as actuator, an Arduino DUE board, an Arduino R3 ethernet shield, a router, a power supply and supporting cables. LabView is used to log test data both from Arduino and analog-signal data acquisition system in DHI. Control algorithm code is in C associated with a real-time clock and executed in Arduino.

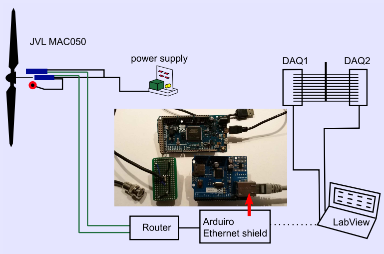

Figure 5: Hardware setup of the control loop.

Wave tank test

According to the time response in irregular wave (Figure 6), the rotor speed is well controlled. C1 has the greatest pitch response as expected.

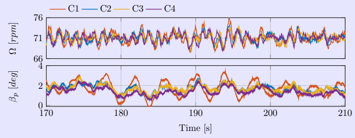

Figure 6: Time responses in irregular wave(sea-state 7).

The power spectral density of measured signals including thrust, rotor speed, blade-pitch, surge and pitch is shown in Figure 7. The identified resonance peaks which correspond to the eigenfrequencies of surge, pitch, wave and rotor speed 3P are marked.

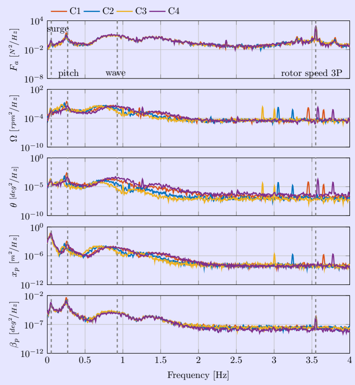

Figure 7: Frequency responses in irregular wave(sea-state 7).

The controller with detuned gains changes the system dynamic properties according to the different resonance frequencies of the rotor speed, blade-pitch and surge from the rotor speed 3P excitation. C4 has greater blade-pitch response but smaller platform-pitch movement.

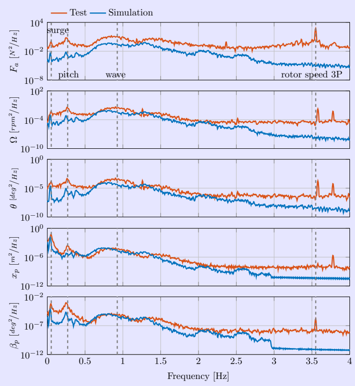

Figure 8: Frequency responses of simulation model and test model in irregular wave(sea-state 7).

Figure 8 shows the comparison of the reduced simulation model and test results in a severe sea-state. The resonance frequencies including surge, pitch and the rang of wave frequencies agree well. The rotor speed 3P excitation isn't replicated since the rotor is modeled as an actuator disk.

Conclusion

A reduced-order simulation model of the scaled floating wind turbine was set up to design the blade pitch controller, which is based on the NREL 5MW baseline controller but with five different gain scheduling methodologies. The controller is later implemented on an Arduino-board to be tested under wind&wave combined environmental loading. The rotor speed is well controlled in different load cases, which shows a good reliability of the simulation model for early controller design.

[1] Sandner, F. (2014) Integrated optimization of floating wind turbine systems. *Proceedings of the 33rd International Conference on Ocean, Offshore and Arctic Engineering OMAE;*.

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