NTNU
Norwegian University of Science and Technology

Consideration of negative aerodynamic damping in the design of floating wind turbines

Carlos E. S. Souza (carlos.souza@ntnu.no), Erin E. Bachynski

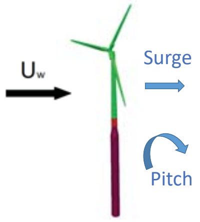
Abstract

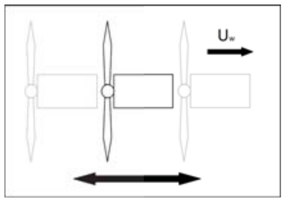
The success of floating wind turbines as feasible solutions for harvesting offshore wind energy still depends on significant cost reductions. An efficient structural design is fundamental, but the strongly coupled dynamics make accurate prediction of the global responses and lifetime estimates challenging. A phenomenon of particular interest is the so-called *aerodynamic damping*, an effect resulting from the interaction between rotor thrust and nacelle motion. This work introduces a method to estimate the magnitude of the aerodynamic damping effect, as a function of the incident wind velocity and the nacelle period of motion. Special focus is given to the conditions where the thrust induces negative damping to the FWT – an effect known to amplify its surge and pitch motions, with dramatic consequences for the integrity of mooring lines and FWT substructure and tower.

Objectives

Develop a method to analyze the interaction between nacelle horizontal motions and rotor thrust.

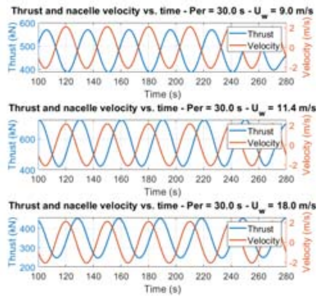
- Apply the above-mentioned method to a 5 MW wind turbine, with different control strategies.
- Estimate the aerodynamic damping coefficients for different operational conditions.
- Provide insight for the preliminary design of floating wind turbines





Methodology

- Forced oscillation of rigid NREL 5 MW rotor, modelled in AeroDyn and coupled to controller.
- U_w covering the entire above-rated operational range; oscillation periods from 20.0 s to 160.0 s, with increments of 1.0 s.
- Control strategies: land-based control gains, detuned gains, variable reference.
- Prediction of damping values based on the phase between time-series of nacelle velocity and rotor thrust.



Thrust as a function of f_0 and ϕ and nacelle velocity/acceleration

$$\dot{x} = \omega x_0 \cos(\omega t)$$

$$T(t) = T_0 + T_{var}(t)$$

$$T_{var} = f_0 \omega x_0 \cos(\omega t + \phi) = f_0 \left[\dot{x} \cos(\phi) + \frac{\ddot{x}}{\omega} \sin(\phi) \right]$$

Nacelle equations of motion

$$m\ddot{x} + c\dot{x} + kx = T(t) \quad \rightarrow$$

$$\left[m - \frac{f_0}{\omega} \sin(\phi) \right] \ddot{x} + \left[c - f_0 \cos(\phi) \right] \dot{x} + kx = T_0$$

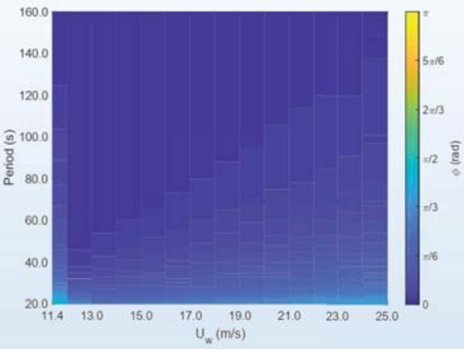
Aer. Damping: $b_{aer} = -f_0 \cos(\phi)$

Blade-pitch control system

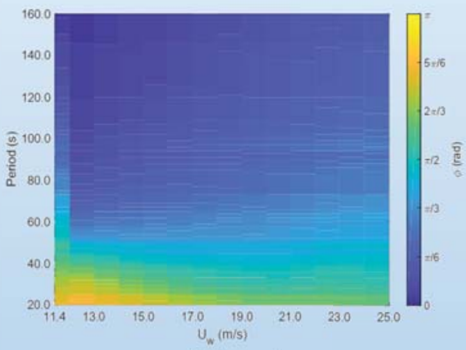
PI controller: $\Delta\theta = K_p \Delta\omega + K_i \int_0^t \Delta\omega dt$

Variable reference: $\omega_r = \omega_0 \left(1 + k\dot{\theta}\right)$

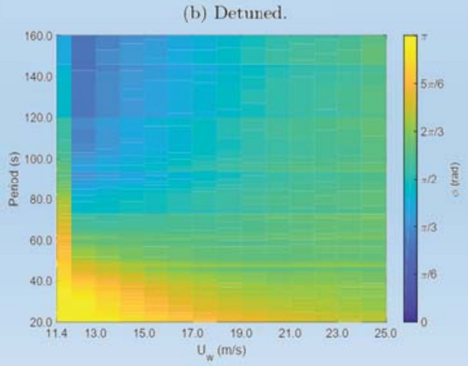
Phase ϕ between nacelle velocity and rotor thrust



(a) Land-based.



(b) Detuned.



(c) Detuned with var. reference.

Results

- When land-based control gains are adopted, the relative phase between nacelle velocity and thrust is always lower than $\pi/2$, leading to negative aerodynamic damping for all combinations of period and phase.
- When the controller is detuned (i.e., the gains are reduced), the phase may be greater than $\pi/2$, for lower wind velocities. The aerodynamic damping then tends to be positive, helping to damp the nacelle motions. As U_w increases, the phase is reduced and the damping eventually gets negative again.
- The combination of detuned gains and variable reference significantly increases the region $\phi > \pi/2$, meaning higher aerodynamic damping for all operational conditions.
- In general, the aerodynamic damping coefficient is higher in magnitude for wind velocities closed to rated.

Conclusions

The aerodynamic damping effect arises from the relative phase between nacelle motion and rotor thrust, and is dependent on nacelle period of motion and incident wind velocity. Damping may be negative in surge and positive in pitch, depending on controller gains, wind velocity and platform natural periods. Blade-pitch controller detuning is more efficient in increasing the damping near rated wind velocity, but its performance is reduced when the velocity increases. Variable reference results in more damping for the entire range of periods and wind velocities.

Aerodynamic damping coefficient (b_{aer})