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Rotor aerodynamics for tank testing of scaled floating wind turbines

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Motivation

Floating structures for offshore wind turbines are a promising alternative to bottom mounted offshore foundations for water depths beyond 50m. A number of countries with deep water areas could expand their potential for offshore sites for renewable energy production. Floating wind turbines could reduce the costs of energy for deep water sites significantly. However, up to date only a few full scale prototypes are in operation. The challenge of state-of-the-art design of floating wind turbine systems is the reliable prediction of the dynamics and the loading in terms of interaction of wind and wave environment. There are many simulation codes in the oil & gas and the wind energy industry available which are validated and proven for either wind or wave loading. But tools which cover both, wind and wave dynamics on the entire floating system, are rare. In this development period scaled model tests can provide valuable data to validate a new generation of simulation tools for floating wind turbines.

Two alternative approaches for scaled rotor aerodynamics

The relevant non-dimensional numbers for physical adequate scaling of floating wind turbines are the Froude (Fr) and Reynolds number (Re). While the Froude number is representing gravity forces and the dynamics of the submerged floating structure the Reynolds number applies for scaled viscous and friction forces of the rotor aerodynamics. Both scaling principles acting directly to contrary direction with respect to geometrical dimensions of the scaled model. In order to match with the hydrodynamics the Froude scaling dominates the model dimensions and masses by compromising correct aerodynamic representation. Within the presented test campaign two rotor model approaches have been analysed to improve the opposed effects of water and air impact on a scaled model:

Froude scaled rotor

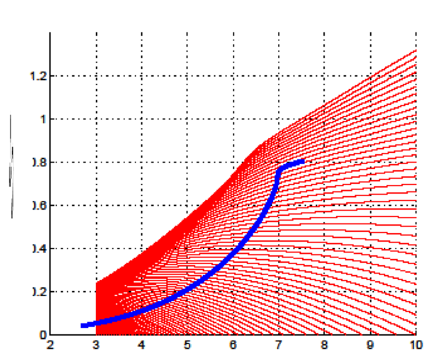
Correct Froude-scaling of
- Rated rotor speed Ω
- Wind speed v_0
- Thrust force F_{thrust}

Set thrust coefficient c_T through blade pitch angle θ s.t.

$$F_{thrust} = \frac{1}{2}\rho\pi R^2 c_T\left(\frac{\Omega R}{v_0}, \theta\right) v_0^2$$

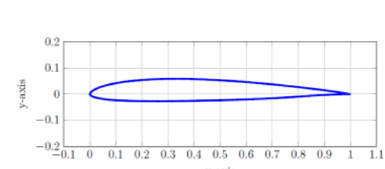
for the given rotor radius R.

Property	Scaling Factor
Length	λ
Mass	$\lambda^3 \frac{\rho_{fresh}}{\rho_{salt}}$
Velocity	$\sqrt{\lambda}$
Force	$\lambda^3 \frac{\rho_{fresh}}{\rho_{salt}}$



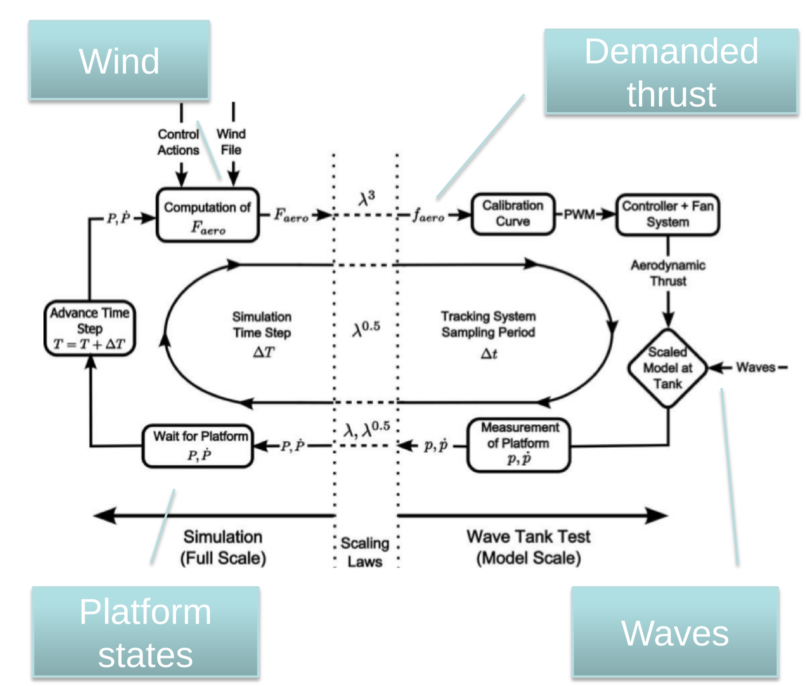
Advantages and disadvantages of Froude rotor scaling

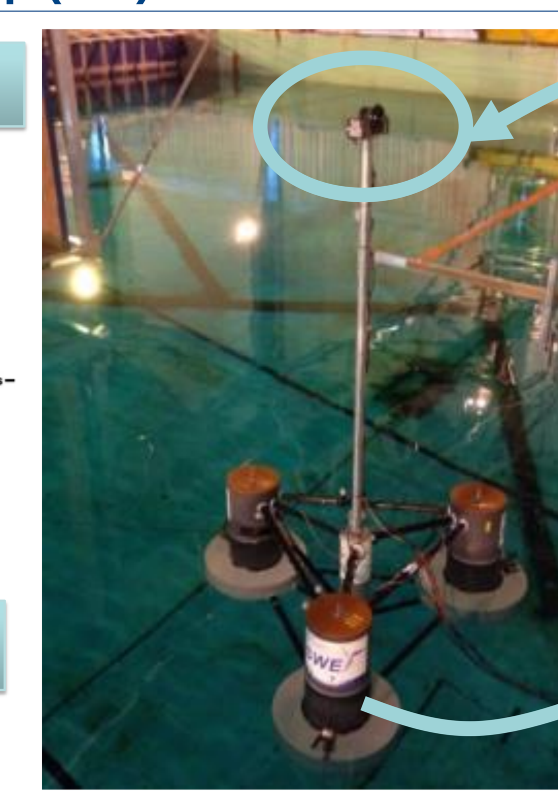
+ thrust, aerodynamic damping
+ 1P, 3P forcing frequencies, gyroscopic forces
+ structural frequencies, deflection due to loads
+ KC number, Lock number
- **Tip Speed Ratio (TSR),** Reynolds number, aerodynamic torque
- generator torque, rotor-tower interaction



Rotor design by Politecnico di Milano

Ducted fan and software in the loop (SIL) control





Sensors at the platform determine the motions at each time step and send them to the simulation code. Here the thrust forces is calculated in real time and forwarded to the ducted fan.

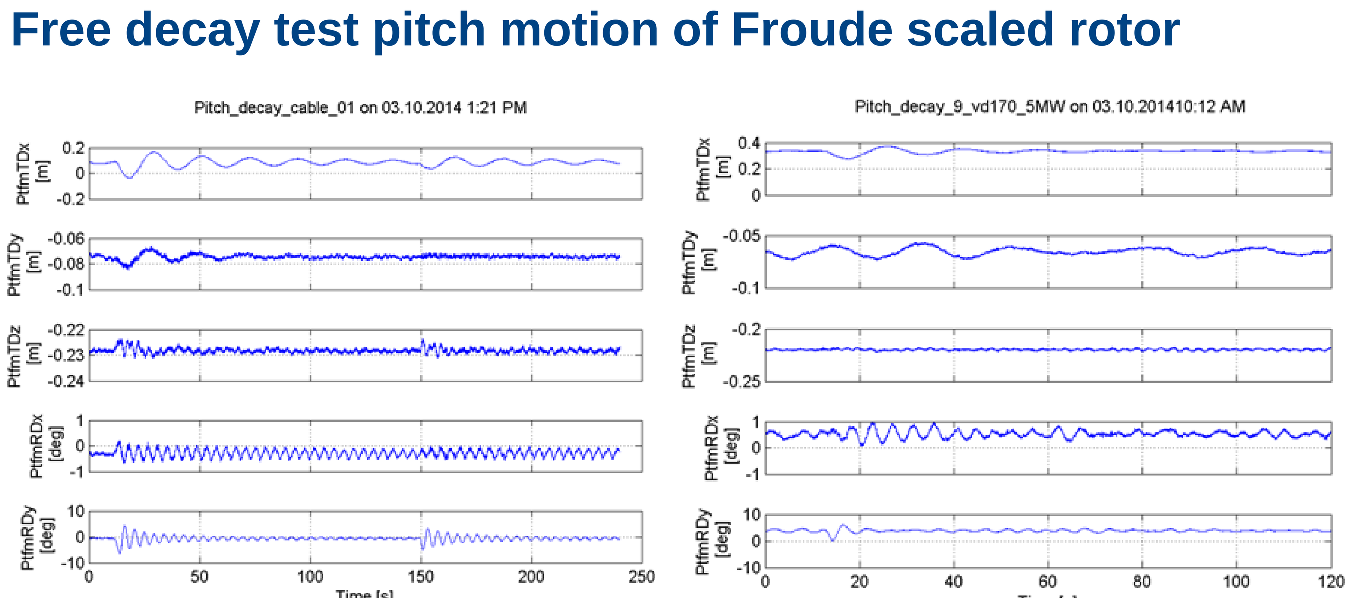
Advantages and disadvantages of Ducted fan (SIL) approach

+ thrust, aerodynamic damping, complex wind load situations, controller influence, cost effective & flexible
- turbulence, gyroscopic effect, aerodynamic torque, generator torque, rotor-tower interaction

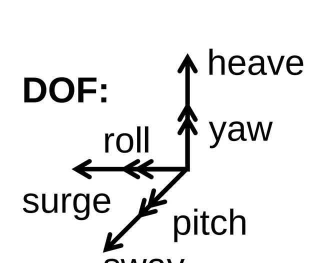
Measurement Results

In October 2014 the INNWIND.EU partners of work package 4.2 performed a measurement campaign at Ecole Centrale de Nantes, France, (LHEEA). The design of the floating model is based on the OC4/DeepCWind semi-submersible with a scaling factor of 1:60 and a 10MW upscale NREL wind turbine on top. Further details are given in [1]. Both rotor models as described above have been tested. For the Froude scaled rotor a wind tunnel with a movable 3x3m² outlet has been applied (wind speed range from 0.5 to 15 m/s).

Free decay test pitch motion of Froude scaled rotor

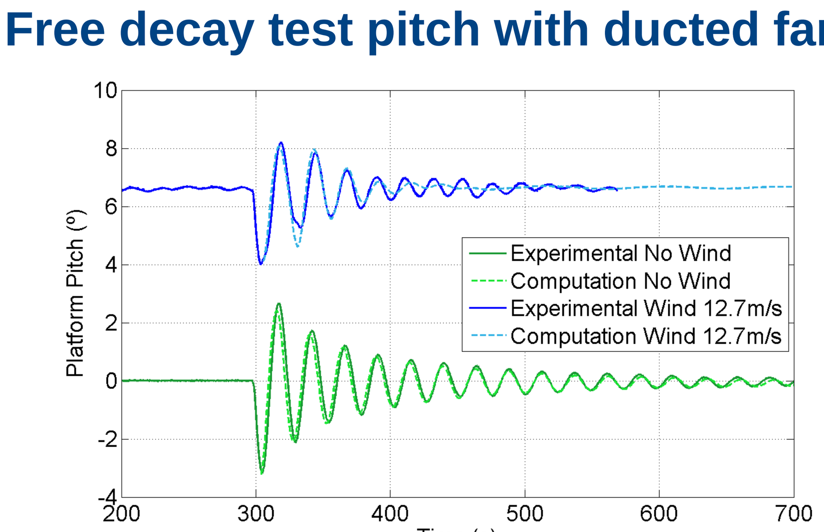


Ptfm-Pitch:
Without cables
With cables



Free decay test pitch with ducted fan (SIL)*

*Measurements and comparison with simulations by CENER

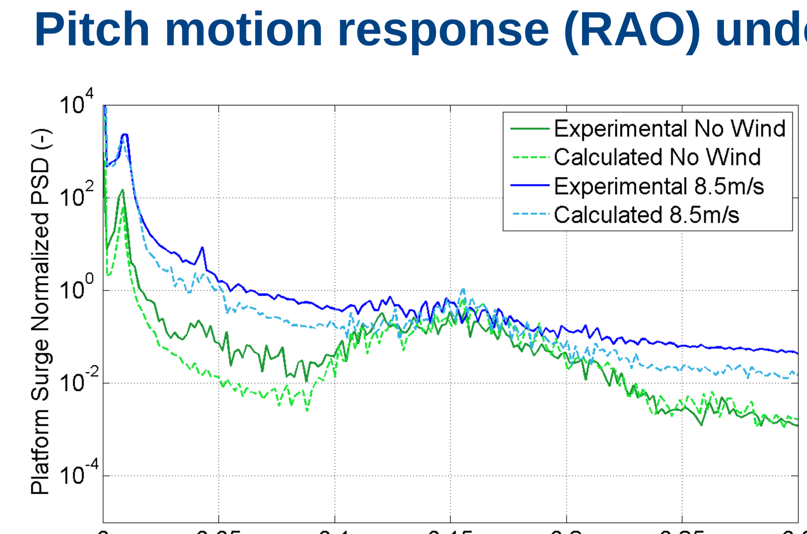


Conditions: No waves, no wind / constant wind

No wind: Amplitude and frequency of floating structure are matching good due to consistent structural design . Good agreement of damping due ducted fan aero thrust.

Wind: Excellent accordance of initial pitch inclination due to corresponding ducted fan thrust force.

Pitch motion response (RAO) under irregular waves & turbulent wind



Conditions: Irregular waves Hs=1.96 Tp=6.5s
no wind / turbulent wind 8.5m/s

No wind: Matches well, except around pitch eigenfrequency, where experiment excitation and response is higher. Low aerodynamic damping makes response at pitch eigenfrequency sensitive to excitation.

Wind: Low frequency response matches better due to low frequency wind loading.

Conclusions

The representation of aerodynamics in todays tank test facilities needs further improvement and comparison with results from high Reynolds number wind tunnel measurements. The software controlled ducted fan (SIL) is a suitable approach to model the main aerodynamic rotor effects simultaneous to wave dynamics – thrust and aerodynamic damping in line with controlled wind speeds. Modeling of rotor torque and gyroscopic effects (and corresponding roll motion) still remains a shortage of todays tank testing configurations.

A complete set of test data will be published on www.INNWIND.EU.

References

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2. J. Azcona, F. Bouchotrouch, M. González, J. Garciandía, X. Munduate, F. Kelberlau and T. A. Nygaard, "Aerodynamic Thrust Modelling in Wave Tank Tests of Offshore Floating Wind Turbines Using a Ducted Fan," J. Phys.: Conf. Ser. 524 012089, 2014.

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