FOWT wave-wind testing with non-Froude wind turbine scaled models

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Abstracts

The scaling law that is commonly used for testing floating offshore wind turbines in wave tank facilities assumes the same Froude number (Fr) for the full-scale and the scaled models. This results in a large mismatch in the Reynolds number (Re) and consequently in highly different model rotor aerodynamics. This paper proposes an innovative way of scaling, here referred to as "aerodynamic scaling".

1. Introduction

Letting n_l be the geometry scaling, the "aerodynamic scaling" involves scaling time with $n_t = 2n_l$.

Quantity	Symbol	Scaling factor	
		Fr scaling	"Aerodynamic scaling"
Reynolds number	Re	$n_l^{1.5}$	$\frac{1}{2}n_l$
Froude number	Fr	1	$\frac{1}{4}n_l^{-1}$
Mach number	Ma	$\sqrt{n_l}$	$\frac{1}{2}$

Table 1: Fr scaling vs. "Aerodynamic scaling"

PRO

❖ Models are characterized by a lower Re mismatch (see Table 1): better quality of the aerodynamics and proper fluid kinematics (same tip speed ratio) [1].

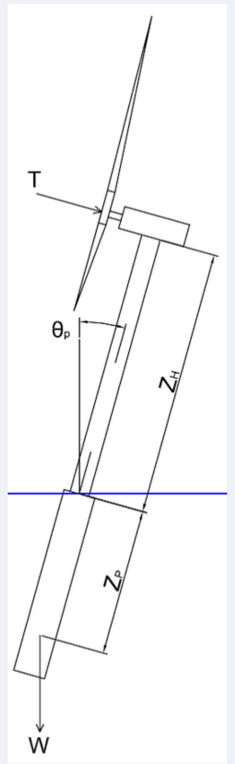
❖ Unlike Fr scaling, model blades chord can be kept unchanged: possible to equip the model with aero-elastically scaled blades [2] and perform tests focused on FOWT aero-servo-hydro-elasticity.

❖ Possible to reuse wind tunnel wind turbine models.

CONS

❖ Model Fr is not preserved (see Table 1): model restoring forces due to gravity are $1/4n_l$ times lower than what is required to balance the aerodynamic forces.

❖ Under the hypothesis of full-linear dynamic system, model platform displacements are $1/4n_l$ times greater than the full-scale ones.



Simple example ($\sin\theta_P = \theta_P$):

- Thrust force: $T = 1/2\,\rho A V^2 C_T$
- Bodies weight – Buoyancy: $W = Mg$
- Moments equilibria: $TZ_H = W\sin\theta_P Z_P$
- Full-scale platform pitch: $\theta_P^F = \frac{\frac{1}{2}\rho AV^2 C_T Z_H}{MgZ_P}$
- Model pitch: $\theta_P^M = \frac{\frac{1}{2}\rho A n_l^2 V^2 \frac{n_l^2}{n_t^2} C_T Z_H n_l}{M n_l^3 g Z_P n_l}$

	Fr scaling	"Aerodynamic scaling"
$\frac{\theta_P^M}{\theta_P^F}$	$\frac{n_l}{n_t^2} = \frac{1}{1}$	$\frac{n_l}{n_t^2} = \frac{1}{4n_l}$

❖ Mismatch between full-scale and model relative placement of platform modes wrt. rotor harmonic.

A solution that overcomes these drawbacks is here presented.

2. Simulation model

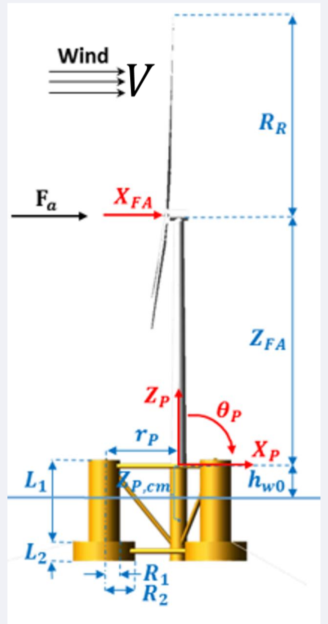
❖ NREL offshore 5-MW Wind Turbine, OC4-DeepCwind floating semi- submersible platform, three slack, catenary lines mooring system.

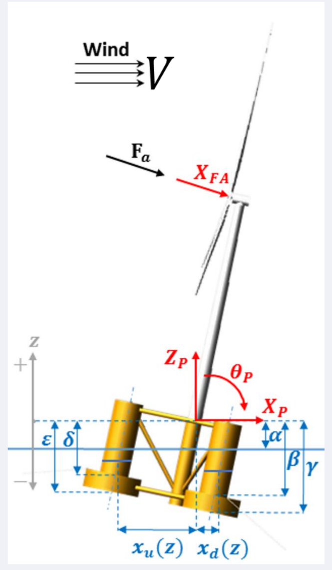
❖ A body mass M_{FA} fixed on top of a massless spring K_{FA} and a damper C_{FA} simulates the dynamics of the first fore-aft tower mode [3].

❖ Four generalized coordinates: $\boldsymbol{q} = \{X_{FA}, X_P, \theta_P, Z_P\}^T$

Non-linear Equation of Motion (EoM):

$$\underbrace{\mathbf{M}_H \ddot{\boldsymbol{q}}}_{\text{hydrodynamic added mass}} + \underbrace{\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\boldsymbol{q}}}\right) - \frac{\partial T}{\partial \boldsymbol{q}} + \frac{\partial V}{\partial \boldsymbol{q}}}_{\boldsymbol{B}} = \boldsymbol{F}_B + \boldsymbol{F}_A + \dots + \boldsymbol{F}_D + \boldsymbol{F}_H + \boldsymbol{F}_M$$





❖ Kinetic and potential energies:

$$T = \frac{1}{2}M_{\mathrm{FA}}\left(\dot{X}^2_{\mathrm{FA,cog}} + \dot{Z}^2_{\mathrm{FA,cog}}\right) + \frac{1}{2}M_{\mathrm{P}}\left(\dot{X}^2_{\mathrm{P,cog}} + \dot{Z}^2_{\mathrm{P,cog}}\right)\dots + \frac{1}{2}I_{\mathrm{P}}\dot{\theta}_P^2,$$

$$V = \frac{1}{2}K_{\mathrm{FA}}X^2_{\mathrm{FA}} + g\left(M_{\mathrm{FA}}Z_{\mathrm{FA,cog}} + M_{\mathrm{P}}Z_{\mathrm{P,cog}}\right)$$

❖ Aerodynamic forces:

λ: Tip speed ratio, β_c: Blade pitch angle

$$\boldsymbol{F}_{\mathrm{A}} = \left\{\begin{array}{c} \frac{1}{2}\rho_a V_{\mathrm{rel}}^2 A C_{\mathrm{F}}(\lambda,\beta_c) \\ \frac{1}{2}\rho_a V_{\mathrm{rel}}^2 A C_{\mathrm{F}}(\lambda,\beta_c)\cos\theta_{\mathrm{P}} \\ \frac{1}{2}\rho_a V_{\mathrm{rel}}^2 A C_{\mathrm{F}}(\lambda,\beta_c) Z_{\mathrm{FA}} \\ -\frac{1}{2}\rho_a V_{\mathrm{rel}}^2 A C_{\mathrm{F}}(\lambda,\beta_c)\sin\theta_{\mathrm{P}} \end{array}\right\}$$

$$V_{\mathrm{rel}} = V\cos\theta_{\mathrm{P}} - \dot{X}_{\mathrm{FA}} - \dot{X}_{\mathrm{P}}\cos\theta_{\mathrm{P}} - Z_{\mathrm{FA}}\dot{\theta}_{\mathrm{P}}$$

❖ Damping forces:

$$\boldsymbol{F}_{\mathrm{D}} = \left\{-C_{\mathrm{FA}}\dot{X}_{\mathrm{FA}}, 0, 0, 0\right\}^T$$

❖ Moorings forces $\boldsymbol{F}_{\mathrm{M}}$ computed with a quasi-static approach [4].

❖ Buoyancy forces: $\mathrm{d}F_{\mathrm{b}}(r) = \frac{\rho_w g\pi r^2}{\cos\theta_P}$

$$\boldsymbol{F}_{\mathrm{B}} = \left\{\begin{array}{c} 0 \\ 0 \\ 2\int_\beta^\alpha \mathrm{d}F_{\mathrm{b}}(R_1)\,\mathrm{d}z + \int_\delta^\alpha \mathrm{d}F_{\mathrm{b}}(R_1)\,\mathrm{d}z + 3\rho_w g\pi R_2^2 L_2 \\ 2\int_\beta^\alpha \mathrm{d}F_{\mathrm{b}}(R_1)x_u(z)\,\mathrm{d}z + 2\int_\gamma^\beta \mathrm{d}F_{\mathrm{b}}(R_2)x_u(z)\,\mathrm{d}z + \dots \\ \dots + \int_\delta^\alpha \mathrm{d}F_{\mathrm{b}}(R_1)x_d(z)\,\mathrm{d}z + \int_\varepsilon^\delta \mathrm{d}F_{\mathrm{b}}(R_2)x_d(z)\,\mathrm{d}z \end{array}\right\}$$

❖ Hydrodynamic forces (Morison's equation):

$$\boldsymbol{F}_{\mathrm{H}} = \left\{\begin{array}{c} 0 \\ 2\int_\beta^\alpha \mathrm{d}F_{\mathrm{w}}(R_1,z)\,\mathrm{d}z + 2\int_\gamma^\beta \mathrm{d}F_{\mathrm{w}}(R_2,z)\,\mathrm{d}z + \dots \\ \dots + \int_\delta^\alpha \mathrm{d}F_{\mathrm{w}}(R_1,z)\,\mathrm{d}z + \int_\varepsilon^\delta \mathrm{d}F_{\mathrm{w}}(R_2,z)\,\mathrm{d}z \\ 2\int_\beta^\alpha \mathrm{d}F_{\mathrm{w}}(R_1,z)z\,\mathrm{d}z + 2\int_\gamma^\beta \mathrm{d}F_{\mathrm{w}}(R_2,z)z\,\mathrm{d}z + \dots \\ \dots + \int_\delta^\alpha \mathrm{d}F_{\mathrm{w}}(R_1,z)z\,\mathrm{d}z + \int_\varepsilon^\delta dF_{\mathrm{w}}(R_2,z)z\,\mathrm{d}z \\ 0 \end{array}\right\}$$

$$\mathrm{d}F_{\mathrm{w}}(r,z) = -\rho_w\left(C_{\mathrm{m}}+1\right)\pi\frac{r^2}{\cos\theta_{\mathrm{P}}}\dot{u}(z) + \rho_w C_{\mathrm{D}} r v(z)|v(z)|$$

$$v(z) = -u(z) + \dot{X}_{\mathrm{P}} + z\dot{\theta}_{\mathrm{P}}$$

$\dot{u}(z), u(z)$: waves acceleration and velocity

❖ The drive-train shaft dynamics equation is added to the EoM:

$$(I_{\mathrm{R}} + I_{\mathrm{g}})\dot{\Omega} + T_{\mathrm{l}}(\Omega) + T_{\mathrm{g}} - \frac{1}{2}\rho_a V_{\mathrm{rel}}^3 A C_{\mathrm{P}}(\lambda,\beta_c) = 0$$

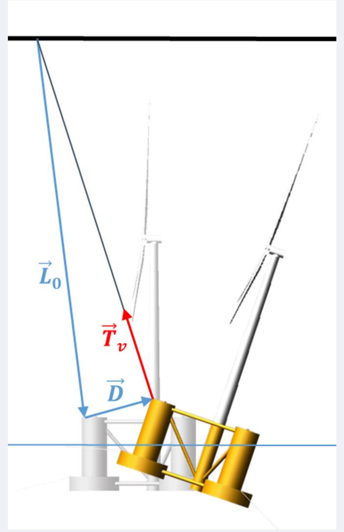
T_g and β_C outputs of torque and pitch closed-loop controllers [4], Ω is the rotor speed.

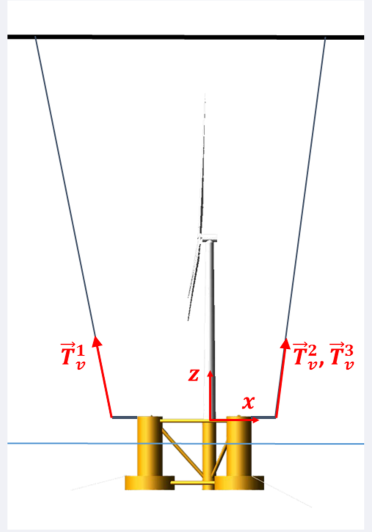
3. Match full-scale platform restoring properties

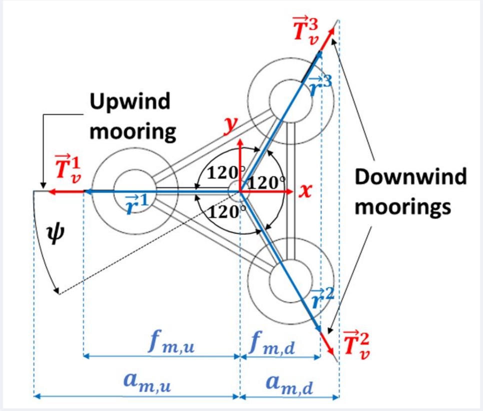
How to improve the model platform restoring properties:

❖ tune the downward moorings mass per unit length μ,

❖ add three pre-tensioned upward moorings connected to the facility ceiling.







EA: stiffness
T_e: pretension

$$\vec{T}_{\mathrm{v}} = -\left|\frac{EA}{\vec{L}_0}\left(|\vec{L}_0 + \vec{D}| - |\vec{L}_0|\right) + T_{\mathrm{e}}\right|\frac{\vec{L}_0 + \vec{D}}{|\vec{L}_0 + \vec{D}|},$$

The following constrained optimization problem

$$\boldsymbol{p}_s^* = \arg\min_{\boldsymbol{p}_s}\sum_{\mathrm{i}=1}^{3} w_\omega^{\mathrm{i}}\left(\frac{\omega_{\mathrm{i}}^F(\boldsymbol{p}_s) - \omega_{\mathrm{i}}^M}{\omega_{\mathrm{i}}^F}\right) + \sum_{\mathrm{i}=2}^{4}\sum_{\mathrm{j}=2}^{4} w_K^{\mathrm{ij}}\left(1-\delta_{\mathrm{ij}}\right)\mathrm{K}^{M,upw}_{\mathrm{ij},\tilde{\boldsymbol{q}}^{M,upw}_{V_r}}(\boldsymbol{p}_s),$$

$$\text{s.t.:}\quad \boldsymbol{g}_s(\boldsymbol{p}_s) \le \boldsymbol{0}, \qquad \left|\frac{\tilde{\boldsymbol{q}}^{M,upw}_{V_r}(\boldsymbol{p}_s) - \tilde{\boldsymbol{q}}^F_{V_r}}{\tilde{\boldsymbol{q}}^F_{V_r}}\right| \le \varepsilon_q,$$

$$\boldsymbol{p}_s = \{f_{m,d}, f_{m,u}, a_{m,u}, a_{m,d}, Te_u, \dots, Te_d, EA_u, EA_d, l_m, \mu\}$$

finds the optimal fairlead f_m and anchor a_m distances from platform center of the upwind $(\cdot)_u$ and downwind $(\cdot)_d$ upward moorings, their line stiffness EA and pre-tension T_e, the ceiling height l_m and the downward moorings mass μ.

Goal is the best possible matching (with small restoring matrix cross-terms) of the full-scale ω_i^F and back-scaled model ω_i^M platform pulsations ($i = 1$: surge, $i = 2$: pitch, $i = 3$: heave), respectively solutions of the problems

$$-(\boldsymbol{\omega}^F)^2\mathbf{M}^F_{\tilde{\boldsymbol{q}}^F_{V_r}} + \mathbf{K}^F_{\tilde{\boldsymbol{q}}^F_{V_r}} = \mathbf{0} \quad , \quad -(\boldsymbol{\omega}^M)^2\mathbf{M}^M_{\tilde{\boldsymbol{q}}^{M,upw}_{V_r}} + \mathbf{K}^{M,upw}_{\tilde{\boldsymbol{q}}^{M,upw}_{V_r}} = \mathbf{0}$$

with

$\tilde{\boldsymbol{q}}^F_{V_r}$ Full-scale: steady equilibria at rated wind speed V_r

$\tilde{\boldsymbol{q}}^{M,upw}_{V_r}$ Model with upward moorings: steady equilibria at rated wind speed V_r

$$\mathbf{M}_{\tilde{\boldsymbol{q}}} = \frac{\partial \boldsymbol{B}}{\partial \ddot{\boldsymbol{q}}}\Big|_{\boldsymbol{q}=\tilde{\boldsymbol{q}}} + \mathbf{M}_{\mathbf{H}}$$

$$\mathbf{K}^F_{\tilde{\boldsymbol{q}}} = \frac{\partial \boldsymbol{B}}{\partial \boldsymbol{q}}\Big|_{\boldsymbol{q}=\tilde{\boldsymbol{q}}} - \frac{\partial \boldsymbol{F}_{\mathrm{B}}}{\partial \boldsymbol{q}}\Big|_{\boldsymbol{q}=\tilde{\boldsymbol{q}}} - \frac{\partial \boldsymbol{F}_{\mathrm{M}}}{\partial \boldsymbol{q}}\Big|_{\boldsymbol{q}=\tilde{\boldsymbol{q}}}$$

$$\mathbf{K}^{M,upw}_{\tilde{\boldsymbol{q}}} = \frac{\partial \boldsymbol{B}}{\partial \boldsymbol{q}}\Big|_{\boldsymbol{q}=\tilde{\boldsymbol{q}}} - \frac{\partial \boldsymbol{F}_{\mathrm{B}}}{\partial \boldsymbol{q}}\Big|_{\boldsymbol{q}=\tilde{\boldsymbol{q}}} - \frac{\partial \boldsymbol{F}_{\mathrm{M}}}{\partial \boldsymbol{q}}\Big|_{\boldsymbol{q}=\tilde{\boldsymbol{q}}} - \frac{\partial \boldsymbol{F}_{\mathrm{M,upw}}}{\partial \boldsymbol{q}}\Big|_{\boldsymbol{q}=\tilde{\boldsymbol{q}}}$$

Constraints $\boldsymbol{g}_s(\boldsymbol{p}_s) \le 0$ prevent collision of upward moorings with model blades for a wide range of platform motions.

4. Simulation results

❖ Simulations of full-scale and model ($n_l = \frac{1}{45}$) free-decays and responses to irregular waves ($H_S = 3.37\ m, T_S = 7.03\ s$) with ODE of Matlab.

❖ Steady wind V_r (approx. $11\ m/s$ for full-scale).

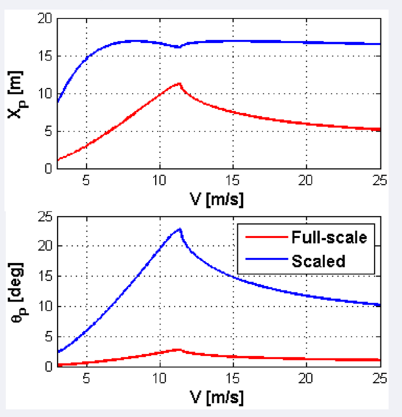
❖ Waves scaling: $\dot{u}^M = 1/2\,\dot{u}^F$ and $\ddot{u}^M = 1/4n_l\,\ddot{u}^F$.

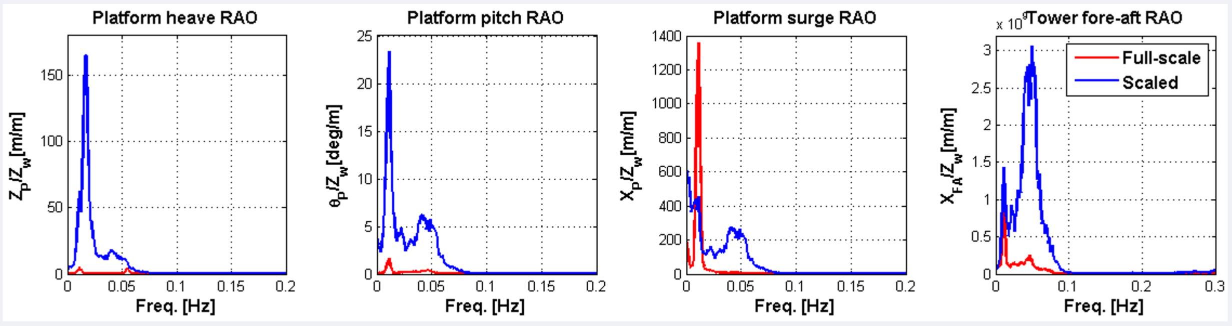
WITHOUT UPWARD MOORINGS

Significant mismatch between full-scale and model:

❖ equilibria $\tilde{\boldsymbol{q}}$ over wind speed

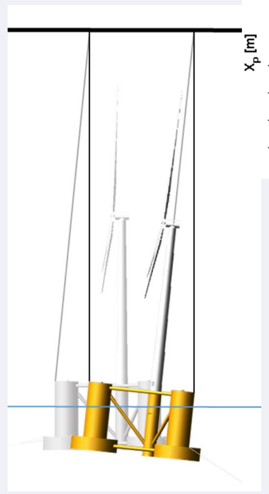
❖ platform and tower RAOs

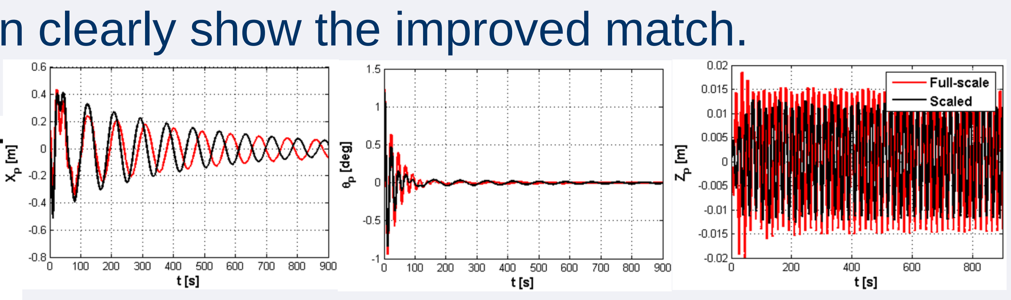




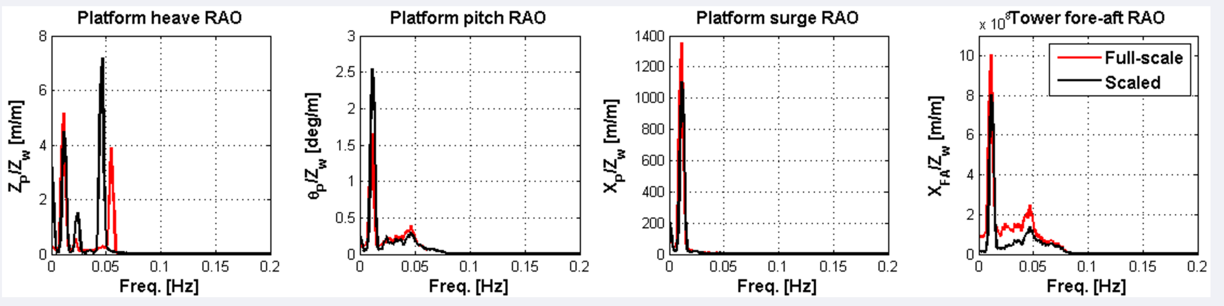
WITH UPWARD MOORINGS AND TUNED μ

The RAOs and time histories of the platform motions during a free decay simulation with an initial pitch perturbation clearly show the improved match.





- The optimal configuration that provides these results is depicted on the figure.
- Upward moorings properties: $Te_u = 75\ N$, $Te_d = 50N$, $EA_u = 1.52 \cdot 10^4\ N/m$, $EA_d = 1.70 \cdot 10^4\ N/m$, $l_m = 4.1\ m$.



5. Conclusions

- Measures to overcome the mismatches are neither expensive nor complicated.
- Useful approach for tests focused on wind turbine aeroelasticity, control and CFD validation.
- Same wind turbine models used for wind tunnel tests can be used also in wave-wind tank tests.

References

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