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Simplified wind turbine models for floating substructure design

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EERA DeepWind CONFERENCE 2025

Introduction

Floating wind projects involve several design partners: floater, mooring and Inter-Array Cables (IAC) designers, Wind Turbine Generator (WTG) OEM, transport & installation (T&I), operation & maintenance (O&M), project owners… Many of whom need to perform numerical simulations of these highly coupled systems.

On the floater and mooring side, initial design loops can be difficult due to the lack of subpart details, as currently WTG Rotor Nacelle Assembly (RNA) model sharing is quite difficult – mostly for industrial data protection reasons around blade properties and controller details.

Thus, **simplified RNA models are valuable and sometimes necessary for substructure designers**, especially at the early project stage. **Such models allow to carry out quick iterations for design & optimization purposes** efficiently, autonomously and with sufficient accuracy, typically when performing mini Integrated Load Analysis (ILA) or sensitivity studies.

Over the years, acting as floating substructure designer on multiple projects, we developed 3 different approaches, each with its application domain but encapsulating most early design needs on governing Design Load Cases (DLC). **They only need commonly shared WTG specification data to be implemented**.

I. Constant Thrust method

Simple but effective method for power production cases. Here verified against a full aeroelastic ILA for the 15 MW IEA wind turbine on a semi-sub floater, in oceanic environmental conditions.

Method - in a nutshell

Reducing the RNA to a combination of lump mass/inertia plus a constant downwind thrust force (and optionally a generator resistant torque). Taking the thrust values from the WTG OEM spec operating curves (using peak-shaving) and applying factors to match global performance parameters for the 3 wind speed regions.

Application domain

The target of the method is the IEC* **1.6 DLC family,** power production cases for Ultimate Limit State (ULS).

**Ref.: IEC61400-3-2 Design requirements for floating offshore wind turbines*

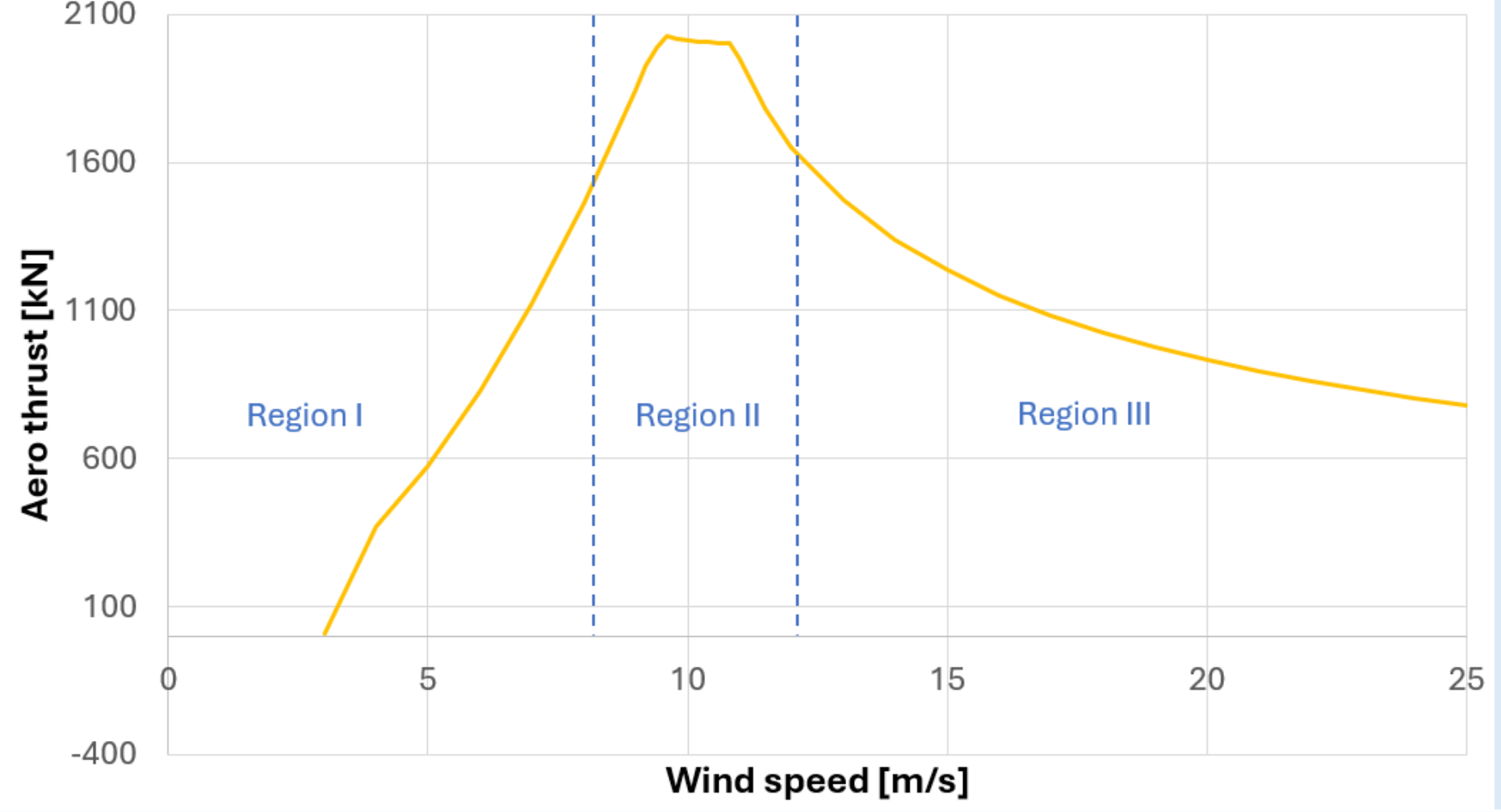
Results & observations

- For design-governing cases [regions 2 & 3], a factor of 100% on the thrust value shall be applied.
- Region-averaged errors sit well below 5% for substructure governing quantities (response maxima).
- Suitable at pre-design stage to assess maximal tilt and tower base moment.

Limitations

- The type of environment (oceanic) presently used likely impacts the verification results: for a site with milder waves, the accuracy may decrease.
- The floater used to carry the study is a VolturnUS-like type of semi-submersible with a spread-out catenary mooring system. Different technologies may see varying verification results.
- Missing turbine induced torsional loads resulting in smaller floater yaw dynamics.

Aerodynamic thrust curve IEA 15 MW turbine with peak-shaving

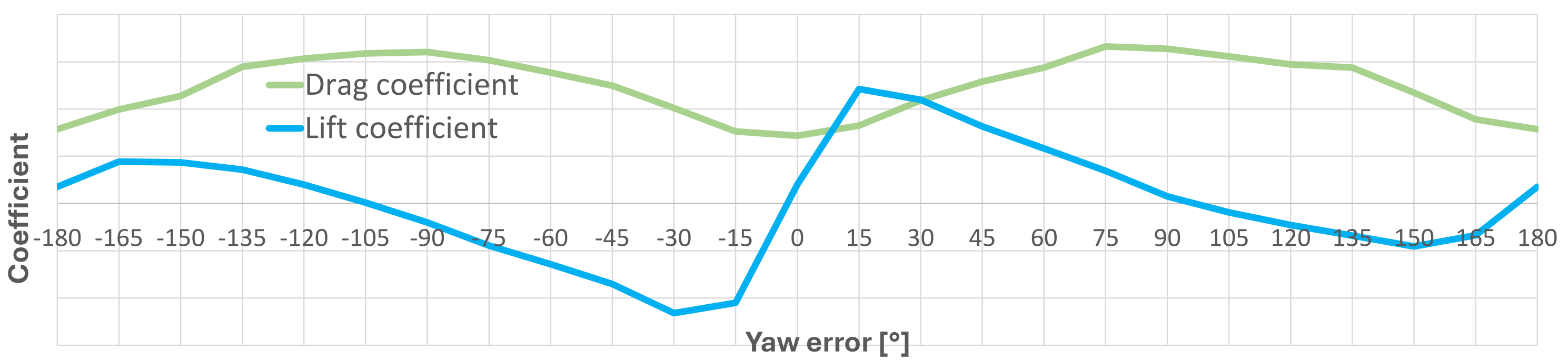


Best predicting thrust factor per wind speed region and observed variable*

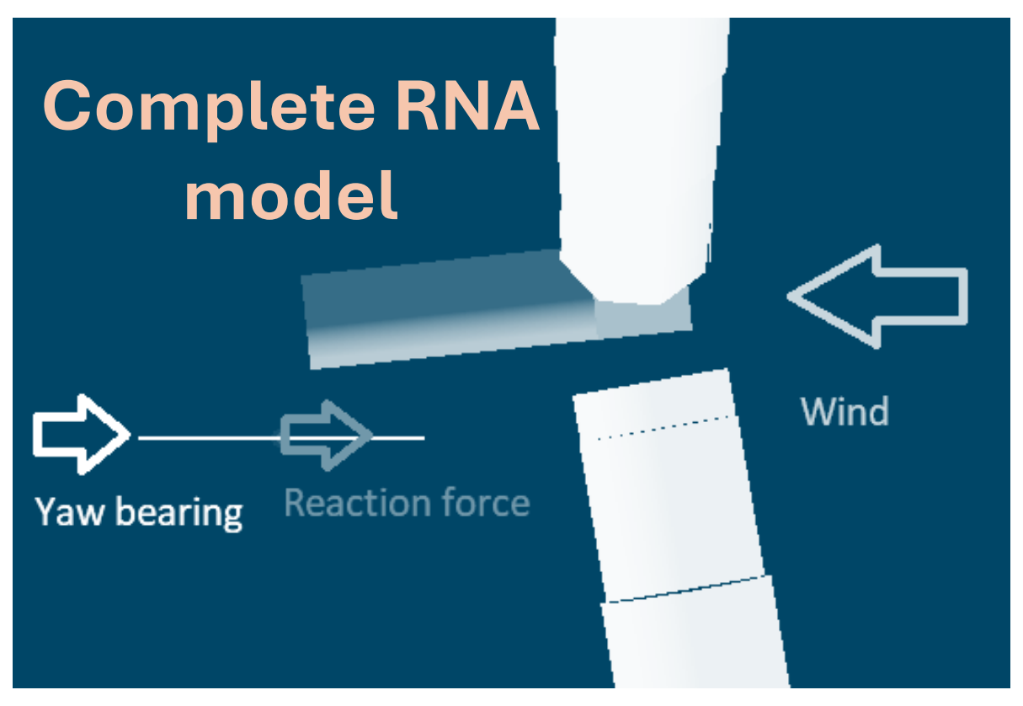
Parameter		Average difference vs. aeroelastic reference [%] for each wind region		
		Wind speed 3 to 7 m/s	Wind speed 9 to 11 m/s	Wind speed 13 to 25 m/s
Thrust factoring rule for best prediction		120%	**100%**	**100%**
Tower base moment	Mean	-	-3.5 %	-14.9 %
	Max**	-0.7 %	**0.5 %**	**-0.6%**
Nacelle fore/aft acceleration	Mean	-	-	-
	Max**	-7.1 %	**-4.6%**	**-1.0%**
Tilt	Mean	-	-3.7 %	-16.3 %
	Max**	0.3 %	**3.5 %**	**2.2 %**
Offset	Mean	-	-0.8 %	0.8 %
	Max**	-2.0 %	-4.7 %	-1.3 %
Fairlead tension (most loaded lines)	Mean	-	-0.7 %	0.1 %
	Max**	-5.0%	-4.8 %	-1.6 %

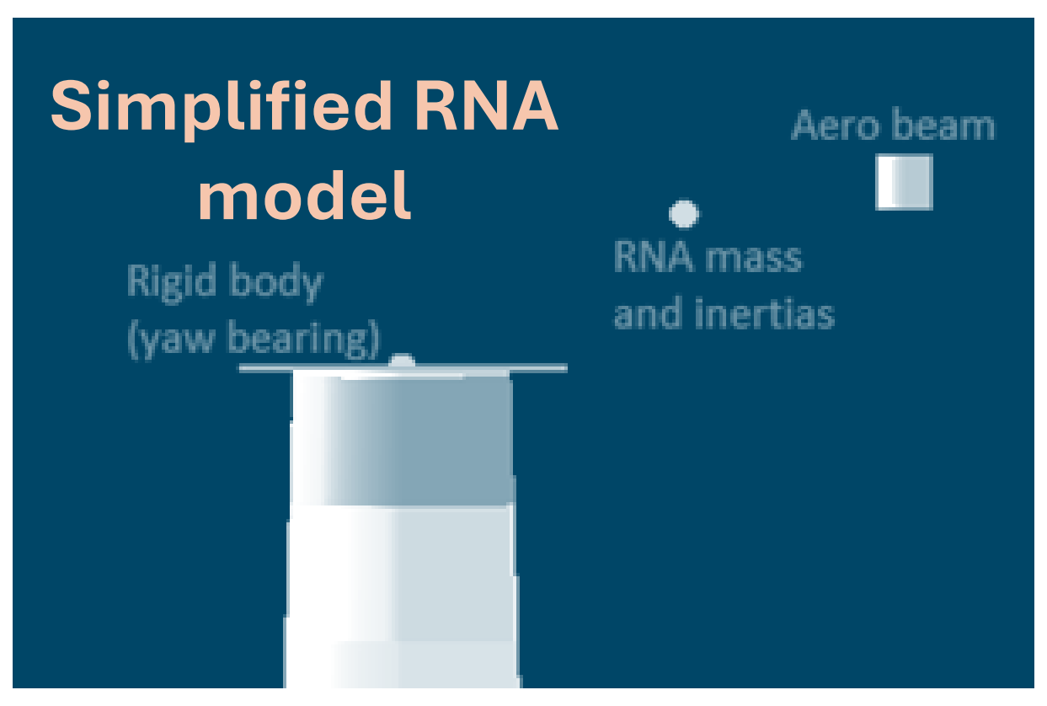
**Without the optional generator resistant torque*
***Presented results are calculated for the characteristic values [mean of maxima] for 1-hour net duration analyses over 6 seeds*

Typical RNA coefficient calibration vs. yaw error*



**Calibration for 30m/s wind speed, clamped RNA and 15° increments*





Maximum relative error (% - absolute values)**

DLC family type	Tower base moment	Nacelle fore/aft acceleration	Tilt	Offset	Fairlead tension (most loaded lines)
6.1	**2.8 %**	**1.9 %**	**1.2 %**	0.7 %	2.4 %
6.2	**0.9 %**	**4.1 %**	**2.9 %**	0.5 %	3.3 %
6.X***	**3.1 %**	**3.8 %**	**3.0 %**	0.3 %	2.6 %

***Presented results are calculated for the characteristic values [mean of maxima] for 1-hour net duration analyses over 6 seeds*
****Sensitivity study with larger wind velocities and wind/wave misalignment*

II. Lift & Drag method

For parked cases. Originally developed by Naval Energies and accepted henceforth by mainstream WTG OEMs.*

**Ref.: IOWTC2020-3516 - Simplified aerodynamic loading model for non-production conditions for floating wind systems design*

Method - in a nutshell

- Reducing the RNA to a lump mass/inertia plus a single aerodynamic element reacting to the wind field.
- Global RNA drag and lift coefficients calibrated from the WTG OEM spec yaw bearing forces as a function of yaw error, respectively parallel and perpendicular to the wind; the latter (global lift) is key for a parked rotor.

Application domain

Parked cases, notably IEC **6.1, 6.2 & 6.4 DLC families**: fit for simulating coupled idling/standstill DLCs for substructure component design.

Results & observations

- Errors sit well below 5% for substructure governing quantities: tower base moment, exposed mooring line tension, offset, and platform tilt.
- Suitable for optimization stages of design, especially valuable for mooring / IAC design and T&I.

Limitations

- Verifications on VolturnUS-like type of semi-submersible (from 6 to 15 MW) with spread catenary moorings, in idling condition.
- A platform yaw inaccuracy may create a divergent trend due to the steep lift slope at small yaw error.

III. Drag Disk in Space-Averaged Wind (SAW) method

Reactive thrust model for power production, incorporating cyclic aero loads for fatigue. A variant / sensitivity study reflects the ongoing research.

Method - in a nutshell

- RNA aerodynamic load modelled thanks to “drag” coefficient polar curves (and no global RNA lift), using:
    - ➢ RNA (rotor) operating aerodynamic thrust for nacelle yaw error 0°, from WTG OEM spec
    - ➢ No loading for nacelle yaw misalignments above 90° ($\cos^2$ interpolation between 0° and 90°)
- Full-grid or swept area space-averaged wind (SAW) field to restore the revolving rotor turbulence smoothing effect.
- Rigid tower to avoid unphysical over-excitation of tower bending by the effect of the wind spectrum tail.

Application domain

This model is intended for power production cases and Fatigue Limit State (FLS) analysis i.e. IEC **1.2 DLC family**.

Results & observations

- At present, it is considered fit for mooring fatigue estimates.
- For floater design, although representing a significant improvement compared to simpler constant thrust approach, it is found to be unconservative and should be used with caution (fit for qualitative comparisons).

Limitations

- Results independent from controller. Especially around nominal thrust where the controller aims at avoiding thrust overloads, this method remains proportional to the square of the relative wind speed.
- No 3P/6P synchronous excitation means no vibrations; hence unconservatism in floater fatigue.

Tower base moment 25 yr long-term Damage Equivalent Load (DEL) sensitivity study

Model name	Tower	Wind model	Tower base moment DEL error
[Ref] Full aeroelastic ILA	**Flexible**	**3D full-field**	**[Ref]**
Aeroelastic RNA	Rigid	3D full-field	-15.3 %
Drag disk	Rigid	Hub height wind speed + vertical profile	**34.1 %**
Constant thrust	Flexible	-	**-29.4 %**
Drag disk in SAW	**Rigid**	**Space-averaged [full grid]**	**-22.9 %**
Drag disk in SAW	**Rigid**	**Space-averaged [swept area]**	-16.7 %

Mooring lines 25 yr long-term Damage Equivalent Load (DEL) sensitivity study

Model name	Tower	Wind model	Fairlead tension DEL error (most loaded lines)	Fairlead tension DEL error (other mooring lines)
[Ref] Full aeroelastic	**Flexible**	**3D full-field**	**[Ref]**	**[Ref]**
Aeroelastic RNA	Rigid	3D full-field	1.2 %	1.3 %
Constant thrust	Flexible	-	**-29.9 %**	-58 %
Drag disk in SAW	**Rigid**	**Space-averaged [full grid]**	**2.6%**	6.3 %
Drag disk in SAW	**Rigid**	**Space-averaged [swept area]**	15.6 %	19.5 %

**Precomputed thrust timeseries were also tested but rejected because of their intrinsic unreliability (despite the illusion of accuracy)*

Conclusions

For early project phases, 3 methods to cover all design situations:

For extreme analysis (ULS)

DLC 1.6: Constant thrust method
For optimisation stages, global max error < 5%

DLC 6.1/6.2: Lift & Drag method
For optimisation stages, global max error < 5%

For fatigue analysis (FLS)

DLC 1.2: Drag disk in SAW method
For mooring estimates and floater qualitative comparisons