Part I: Theory of LoFT

Section I Overview:

LoFT (**L**ow-**o**rder modelling of **F**loating **T**urbines) is an open-source framework designed for fast simulations of large amounts of floating offshore wind turbines (FOWTs) [1]. To achieve this, the key principle is to retain the overall system dynamics while minimizing the computational burden. In LoFT, the computational burden is reduced from two aspects: low-order modelling of FOWTs and simplified environmental loads. Moreover, to retain the overall system dynamics, wake effect is considered in the wind field modelling. The validation of LoFT against full-order models in OpenFAST can be found in the Appendix A.

A. Floating Offshore Wind Turbine Modelling

Specifically, for a single FOWT, the low-order model reserves degrees of freedoms (DoFs) that significantly influence the wind power capture, as shown in Fig. 1. The reserved DoFs $\mathbf{q} = [\psi, \theta_p, x_s, x_h]^T$ include the rotor azimuth, the platform pitch θ_p, the platform surge x_s and the platform heave x_h. These DoFs are selected according to experimental results. With these DoFs, in the time domain, the equations of motions can be expressed as:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{F}_{hydro} + \mathbf{F}_{wind} + \mathbf{F}_{moor} \tag{1}$$

Here $\mathbf{M}$ is the mass or inertia matrix, $\mathbf{K}$ is the hydrostatic restoring matrix determined by gravity and buoyancy, $\mathbf{F}_{\text{hydro}}$, $\mathbf{F}_{\text{wind}}$ and $\mathbf{F}_{\text{moor}}$ are the hydrodynamic, aerodynamic and mooring load, respectively.

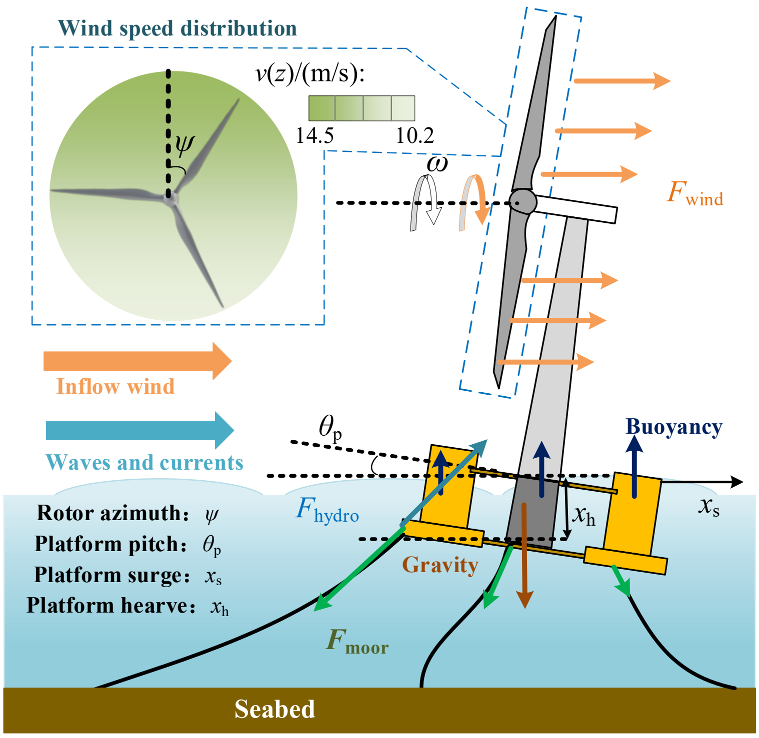


Fig. 1. Low-order modelling of FOWTs

B. Wake Effect

LoFT reduces the computational burden by simplifying the turbine-level modelling. However, to retain the overall system dynamics, in the farm level, wake effect is considered in the wind field modelling

Wake effect leads to a decreased wind velocity in downstream wind turbines, leading to the power reduction in the farm level. LoFT adopts TurboPark to describe the wake effect in an offshore wind farm. TurboPark is a parametric empirical wake model validated on 19 offshore wind farms in the real world [2].

C. Local controllers

In this subsection, the operation of the floating wind turbine is explicitly explained. A diagram of the FOWT control system is presented in Fig. 2. The control system is divided into two main components: a local blade pitch controller, a local generator torque controller.

The local blade pitch controller is designed to stabilize the platform motion and rotor speed of the FOWT in above-rated wind conditions. To achieve these objectives, it employs floating feedback and pitch saturation, thereby reducing rotor thrust variances. The local generator torque controller aims to maintain a stable rotor speed in under-rated wind conditions. There are two types of torque controllers. The first approach follows the "k-ω^2" law, which means its torque output is proportional to the square of the rotor speed. The second approach uses a Proportional-Integral (PI) controller to track the reference rotor speed calculated based on the wind speed. Additionally, a set-point smoother is introduced to ensure a smooth transition between the local blade pitch and torque controllers. More details about the local controller can be found in [3].

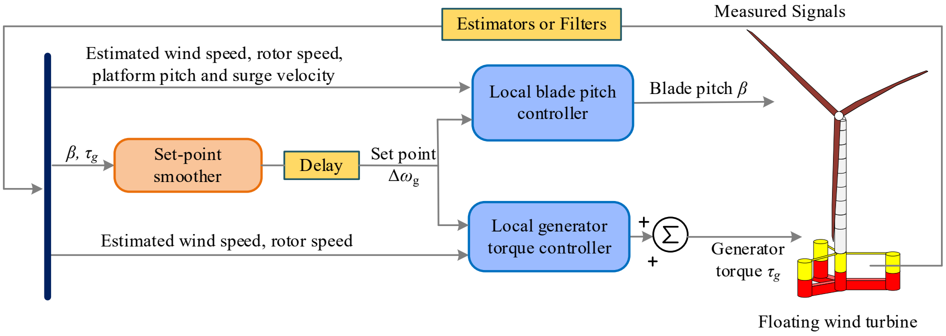


Fig. 2. The local controller of floating turbines

D. Primary frequency response

The primary frequency response of floating offshore wind turbines may lead to large platform motions, especially in above-rated wind conditions. This is due to the infamous negative damping issue, which was originally discussed in [4]. The negative damping issue refers to the phenomenon that the blade pitch actuation to maintain rotor speed will lead to large platform pitch motion. This is worse when an FOWT is participating the frequency regulation, because frequency regulation will lead to large rotor speed variation. Fig. 3 compares the dynamics of an IEA 15 MW semi-submersible FOWT during normal operation and its dynamics when providing frequency response, highlighting the changes in platform motion [5].

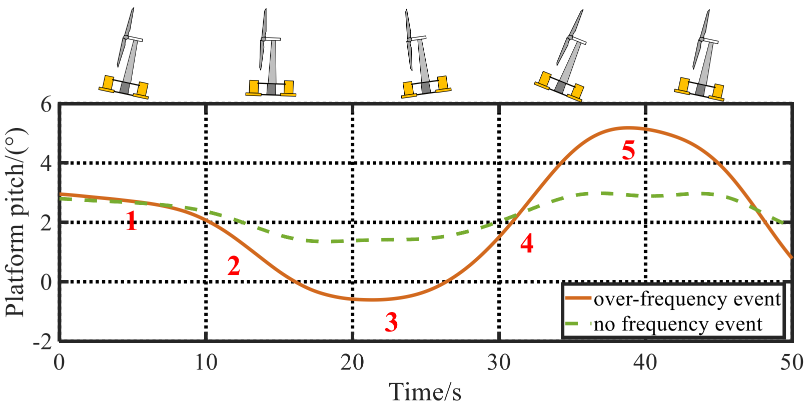


Fig. 3. The platform pitch motion of an FOWT during normal operation or an over-frequency event, obtained with OpenFAST.

References:

[1] M. Mei, P. Kou, Z. Zhang, Y. Zhang, Z. Xue, and D. Liang, “Primary frequency response of floating offshore wind turbines via deep reinforcement learning and domain randomization,” *IEEE Trans. Sustain. Energy*, early access, Mar. 27, 2025, doi: 10.1109/TSTE.2025.3555266.

[2] J. Pedersen, E. Svensson, L. Poulsen, and N. Nygaard, “Turbulence optimized park model with gaussian wake profile,” in *J. Phys. Conf. Ser.*, vol. 2265, no. 2, p.022063. May 2022,

[3] N. J. Abbas, D. S. Zalkind, L. Pao, and A. Wright, “A reference open-source controller for fixed and floating offshore wind turbines,” Wind Energy Sci., vol. 7, no. 1, pp. 53–73, Jan. 2022.

[4] T. J. Larsen and T. D. Hanson, “A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine,” *J. Phys.: Conf. Ser.*, vol.75, no.1, Aug.2007, Art.no.012073.

[5] 梅铭洋,寇鹏,张智豪,等.考虑平台运动的浮式海上风机频率响应控制[J].,中国电机工程学报 2025,45(12): 4681-4693.DOI:10.13334/j.0258-8013.pcsee.232721.

MEI Mingyang, KOU Peng, ZHANG Zhihao et al, Control of Floating Offshore Wind Turbines for System Frequency Response Considering Platform Motions[J]. Proceedings of the CSEE. 2025,45(12): 4681-4693.DOI:10.13334/j.0258-8013.pcsee.232721. (in Chinese)

Section II Examples

Example 1: An Illustrative five-turbine case

This example shows how to change environment settings and simulate five IEA 15 MW semi-submersible FOWTs. The structure of a floating wind turbine is shown in Fig. 4. The output is shown in Fig. 5.

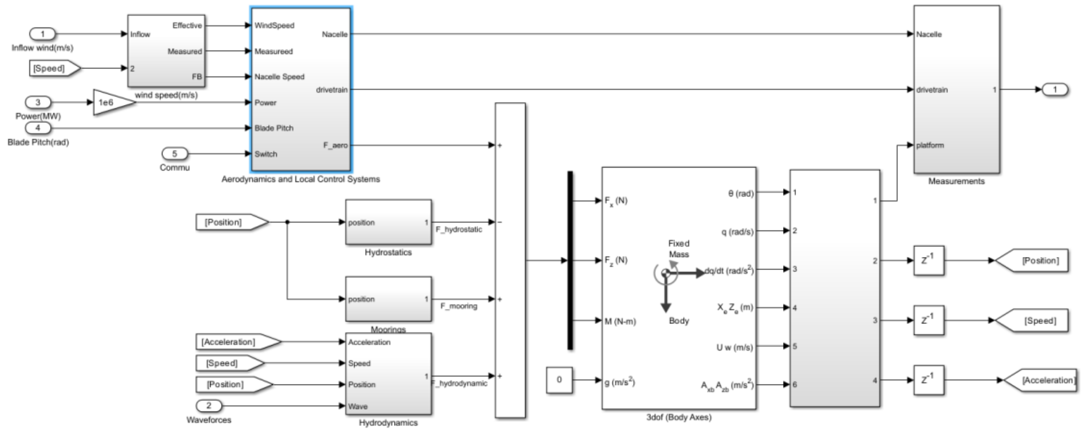


Fig. 4. The structure of a floating wind turbine in LoFT

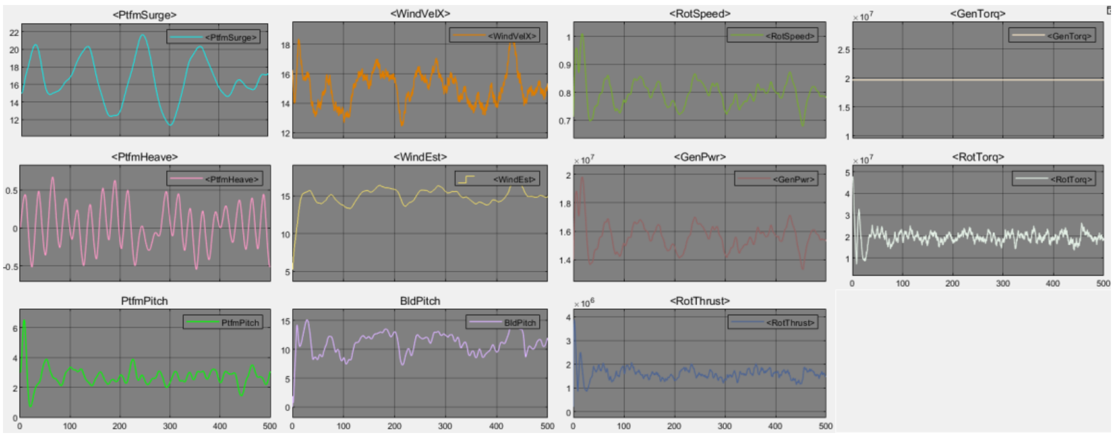
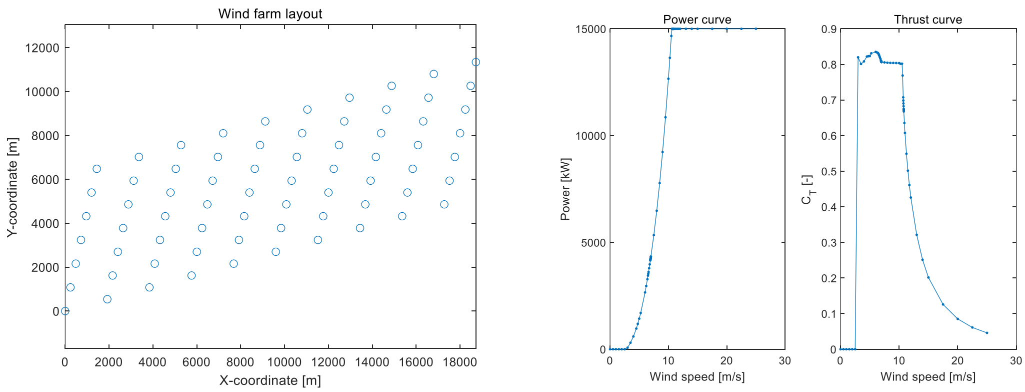


Fig. 5. The floating wind turbine model output in Example 1

Example 2: A 70-turbine Floating Offshore Wind Farm

This example shows how to simulate 70 FOWTs considering wake effect. The layout and turbine power/thrust curves are shown in Fig. 6(a) and Fig. 6(b), respectively. the Time-averaged wind field is shown in Fig.7. The simulation results, including power output and rotor speed, are shown in Fig.8 and Fig. 9. It should be noted that the results may vary due to stochastic wind field generation.



(a) (b)

Fig. 6. Simulation setup in Example 2 (a) layout (b) power and thrust curves of the IEA 15 MW semi-submersible FOWT

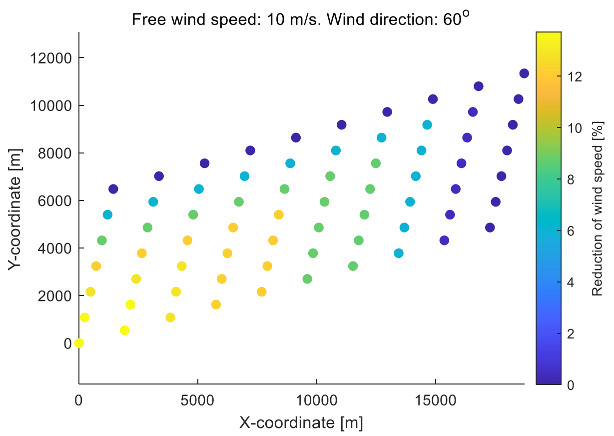


Fig. 7. Time-averaged wind field in example 2 using TurboPark (row 1 on the left)

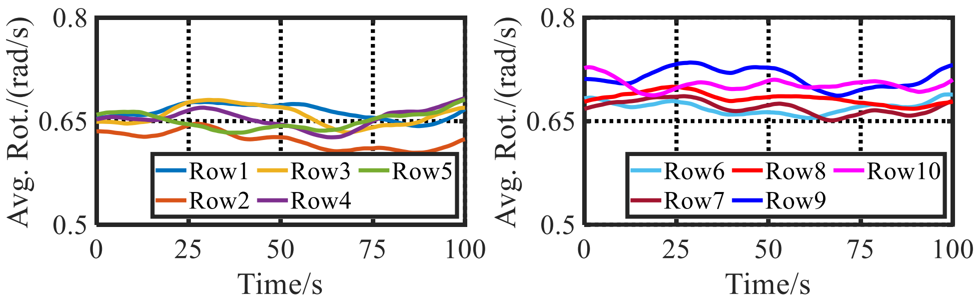


Fig. 8. Average rotor speed of floating turbines in each row.

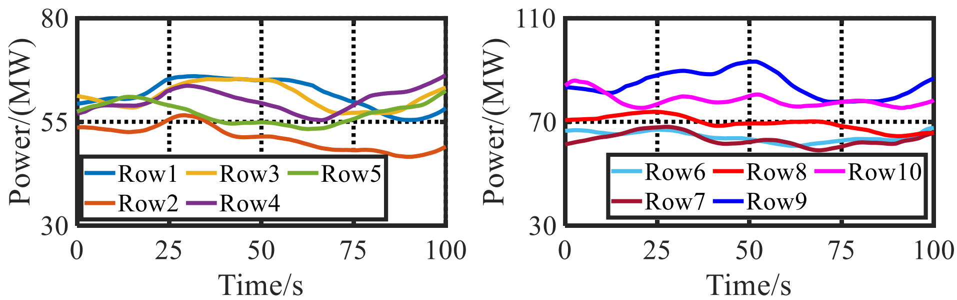


Fig. 9. Power output of floating turbines in each row.

Example 3: Two Floating Offshore Wind Farms Connected with IEEE 39-bus System

In example 3, a modified IEEE 39-bus system is employed, as illustrated in Fig. 10. The system comprises 39 buses, 32 transmission lines, 10 synchronous generators (SGs), and 2 floating wind farms. Automatic generation control (AGC) is activated for the SGs to restore frequency when deviations are less than 0.2 Hz. Furthermore, to emulate a system with high renewable energy penetration, several SGs are replaced by constant power sources, which do not provide primary frequency reserves.

All SGs are thermal units, each with a capacity of 1000 MVA. Among these units, SG 03, SG 07, and SG 10 do not provide primary frequency reserves, while SG 06 and SG 08 participate in AGC. To simplify the simulation, both floating wind farms are assumed to have identical specifications, each consisting of 70 IEA 15MW semi-submersible FOWTs arranged in ten rows, with seven turbines per row, representing a typical radiation topology for such wind farms.

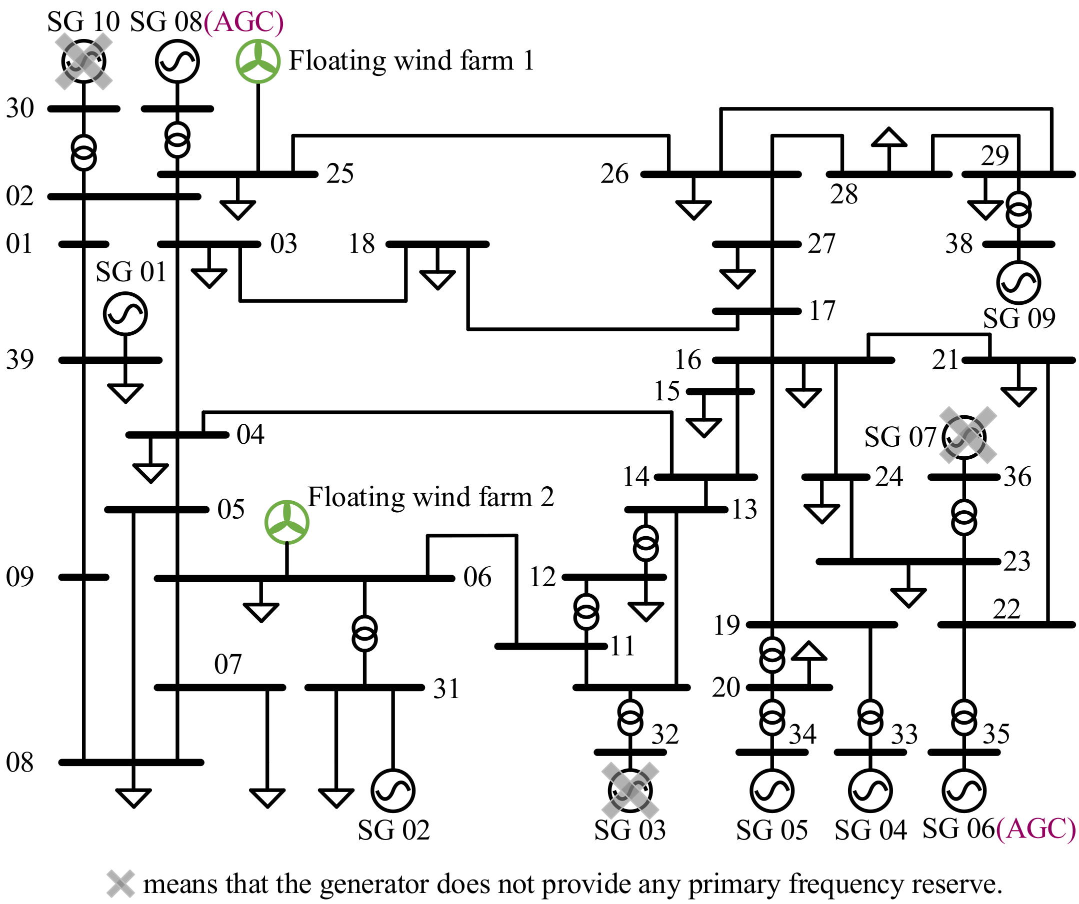


Fig. 10. The modified IEEE-39bus system

Appendix: Validations

A. Validation against full-order models in OpenFAST

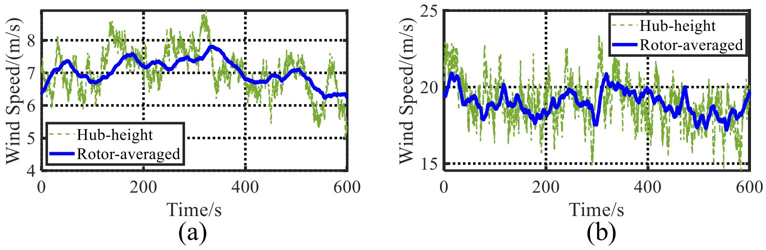


Fig. 11. Hub-height wind speeds and rotor-averaged wind speeds used in the validation (a) below-rated conditions (b) above-rated condition

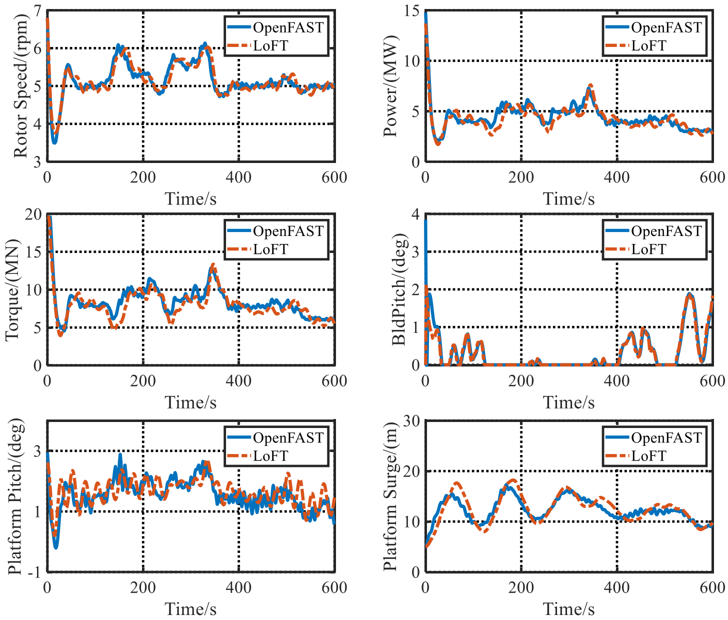


Fig. 12. Validation against full-order models in below-rated wind conditions

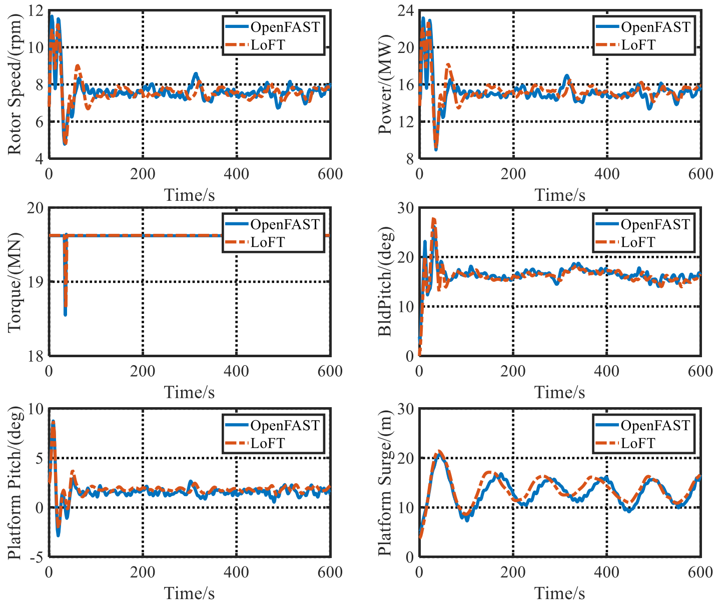


Fig. 13. Validation against full-order models in above-rated wind conditions

Part II: Community Tools for Floating Wind Turbines

LoFT (**L**ow-**O**rder modelling of floating wind turbines **F**or **T**raining) draws on the work of other open-source repositories. Below we give a list of them and collect their links and key features. Hope that this list will help beginners and developers.

Table1. A list of open-source repositories for beginners in the area of floating wind turbines

Repository(link)	Key features	Main Purpose	Developers
OpenFast/Fast.Farm	Individual turbine or wind-farm model (with a limited number of wind turbines) written in Fortran; can simulate steady or turbulent inflow, regular or irregular waves; and conduct structural/fatigue analysis. The resulted are validated by scaled experiments.	Model	NREL
WEC-Sim	Wave Energy Converter Simulator (WEC-Sim), an open-source code for simulating wave energy converters. The code implementations for hydrodynamics and mooring dynamics are similar and helpful for modelling of floating wind turbines.	Model	NREL
RAFT	RAFT - Response Amplitudes of Floating Turbines, python codes for frequency-domain analysis of floating wind turbines. It presents a design-oriented modelling of floating wind turbines	Design	NREL
WISDEM	The Wind-Plant Integrated System Design and Engineering Model (WISDEM) is a set of models for assessing overall wind plant cost of energy (COE). Helpful for design and economic assessment of floating wind turbines	Design	NREL
ROSCO	Reference open-source controller that can be used in OpenFAST; when compiled, produces a libdiscon.so controller that uses a	Control	CU Boulder /NREL

	specified DISCON.IN file. The controller for floating wind turbines features floating feedback, peak saturation and detuned natural frequency.		
Floris	FLORIS is a controls-focused wind farm simulation software incorporating steady-state engineering wake models into a performance-focused Python framework.	Control	NREL
MoorPy	MoorPy is a design-oriented mooring system library for Python based around a quasi-static modeling approach.	Design	NREL
HydroChrono	HydroChrono is an emerging hydrodynamics simulation tool designed to model complex ocean systems. Seamlessly integrated with the Project Chrono physics engine, it offers a powerful C++ API for a wide range of simulations.	Model	NREL
QBlade	Built on the Project Chrono physics engine.	Model	
MOST (link1, link2)	Modelling floating turbines based on Simscape multibody.	Model	MOREnergyLab
TurboPark	TurbOPark is a parametric wake model developed by Ørsted and was validated on 19 offshore wind farms coupled with a blockage and a flow model.	Model	DTU
LoFT	Low-order modelling of floating wind turbines for reinforcement learning training.	Control	XJTU