MARIN

BETTER SHIPS, BLUE OCEANS

EERA DeepWind CONFERENCE 2024

An improved coupled frequency domain model for FOWT

Gijs Bouman

17-01-2024

Introduction (and a question)

How far is floating wind?

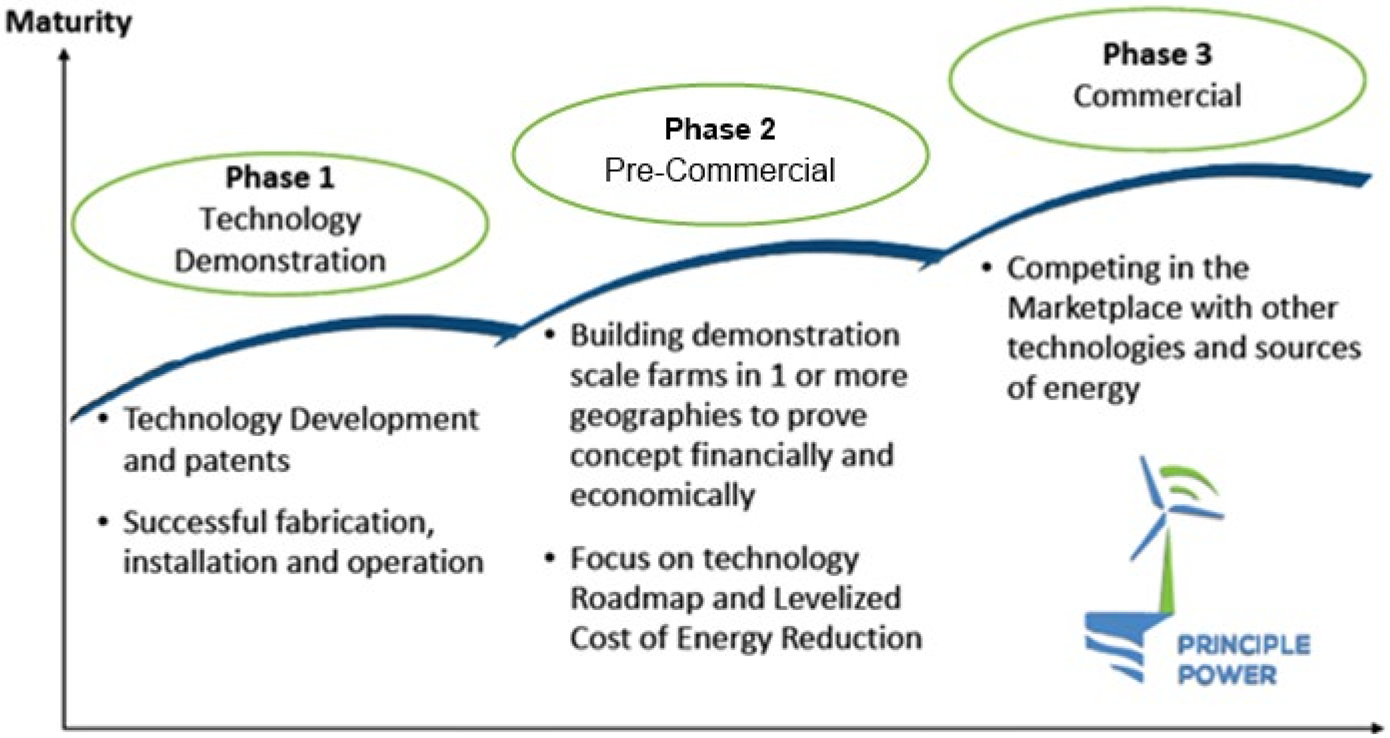

Image source: Principle Power, timeline adjusted by MARIN

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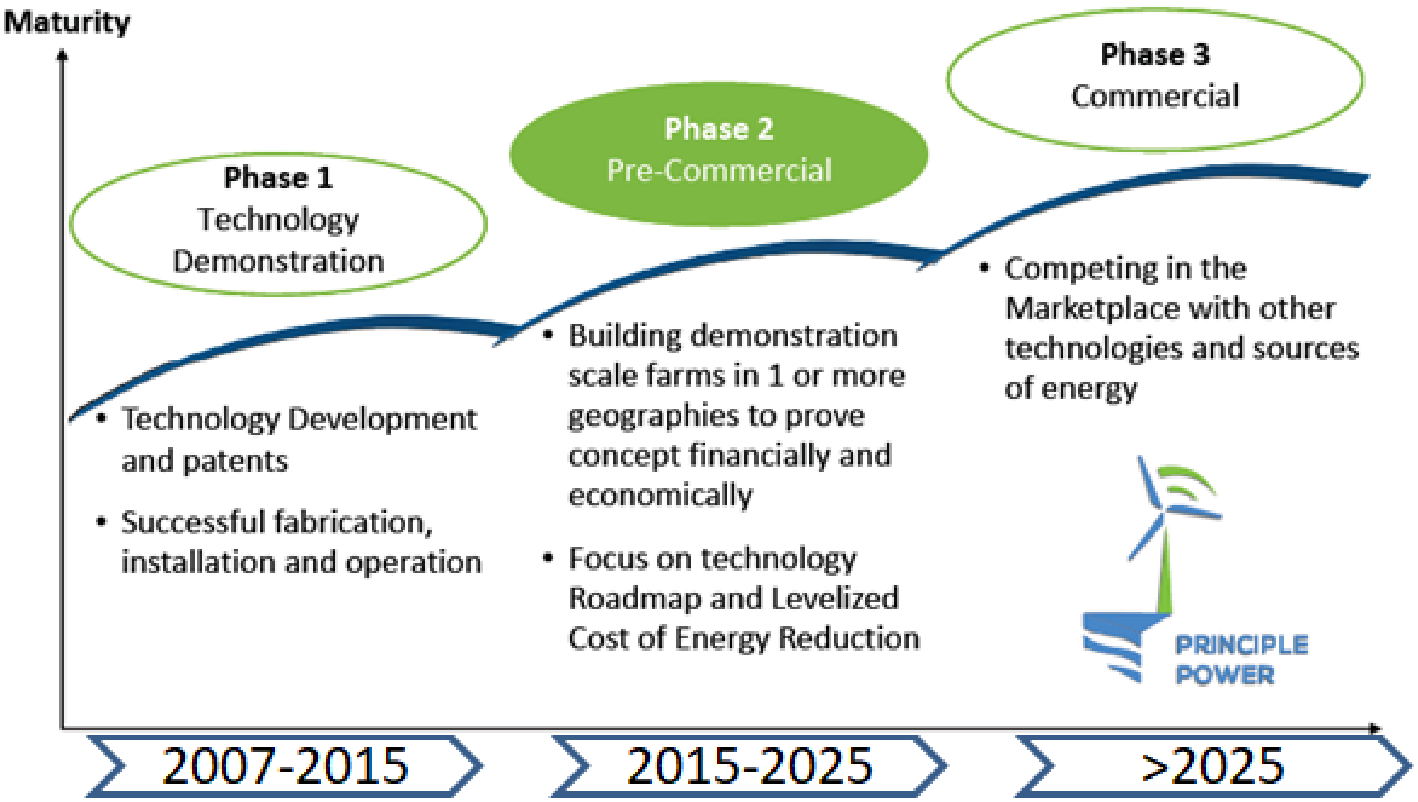


Image source: Principle Power, timeline adjusted by MARIN

How far is FOWT?

- Optimization and push towards commercial phase results in many concepts in:
  - Floaters (type, size, material)
  - Turbines (size, type, blade pitch control)
  - Mooring systems (type, steel/synthetic)
  - Environments (mild/harsh, deep/shallow)





Sources: BW Ideol | Principle power | SBM | Hexicon | X1 Wind

How far is FOWT?

- In commercial phase, still work remaining to size designs for:
  - Environmental conditions (also within farm)
  - Water depth
  - Turbine size

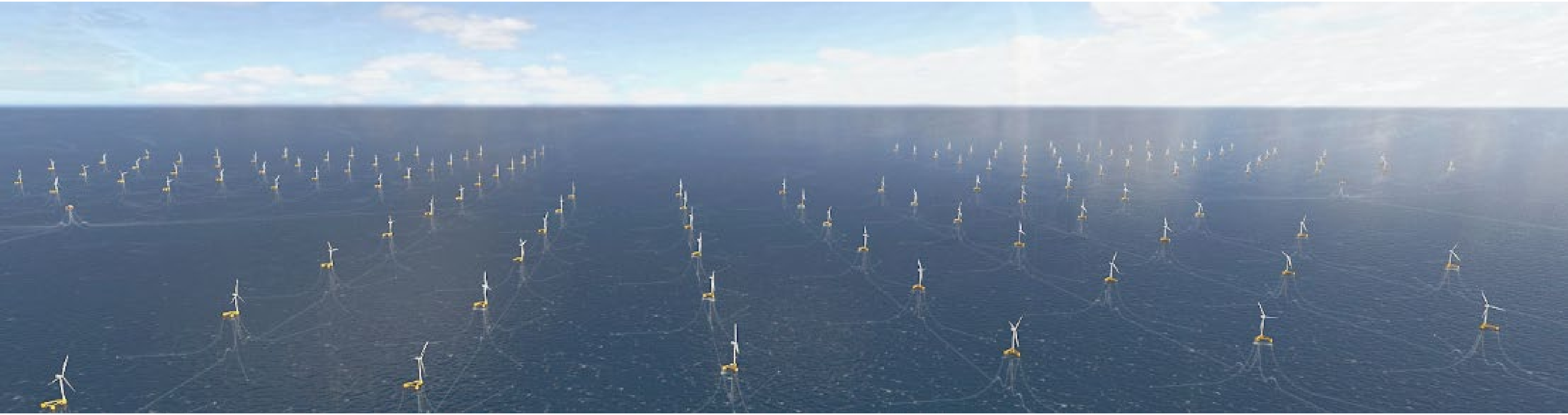
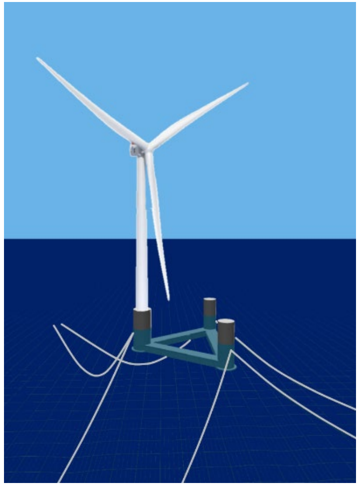


Image source: Korea Floating Wind

Example: sizing of 22MW open-source reference platform

- Parametric design
- Design space screening in frequency domain
- Governing criteria found:
  - Platform tilt in operational sea (wind-dominated)
  - RNA accelerations in survival case (wave-dominated, parked rotor)



	MPM RNA accel. [m/s^2] Survival	MPM pitch angle [deg] Operational
Frequency domain	+2.74	-3.9

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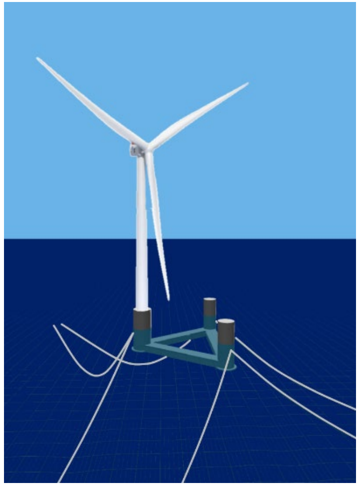
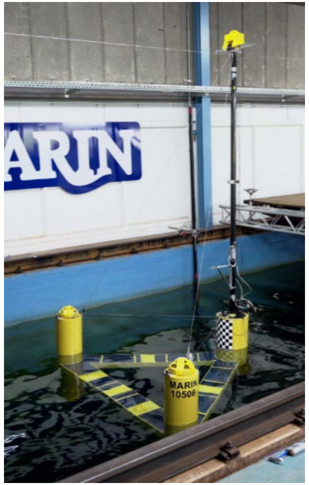
- Validation in time domain and basin test





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Time domain/basin	+2.82	-5.0

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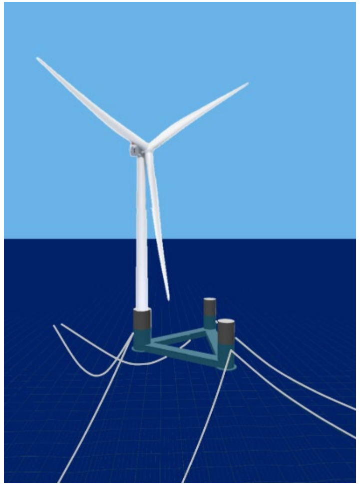

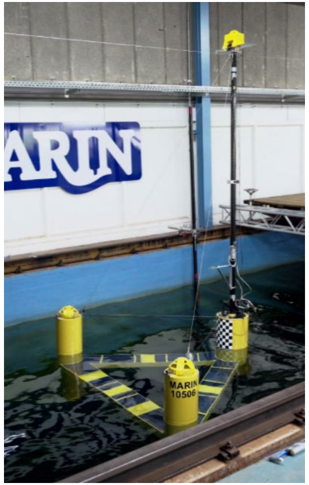

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- Design space screening in frequency domain
- Governing criteria found:
  - Platform tilt in operational sea (wind-dominated)
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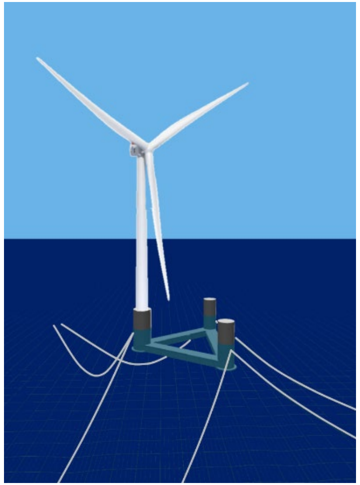
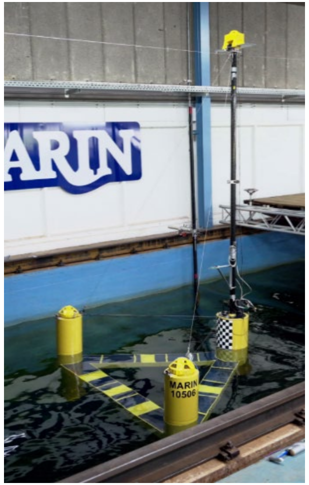
- Validation in time domain and basin test
- Missing dynamics from rotor and controller!





	MPM RNA accel. [m/s^2] Survival	MPM pitch angle [deg] Operational	Aerodynamic modelling
Frequency domain	+2.74	-3.9	Constant force
Time domain/basin	+2.82	-5.0	BEM model, blade pitch controller

For efficient early stage evaluation, we need…

- …an efficient evaluation tool
- …to resolve the coupled aero-hydro-servodynamic response
- …the floater motion spectra
- …mooring line tension spectra

Methodology

RAFT: Response Amplitudes of Floating Turbines

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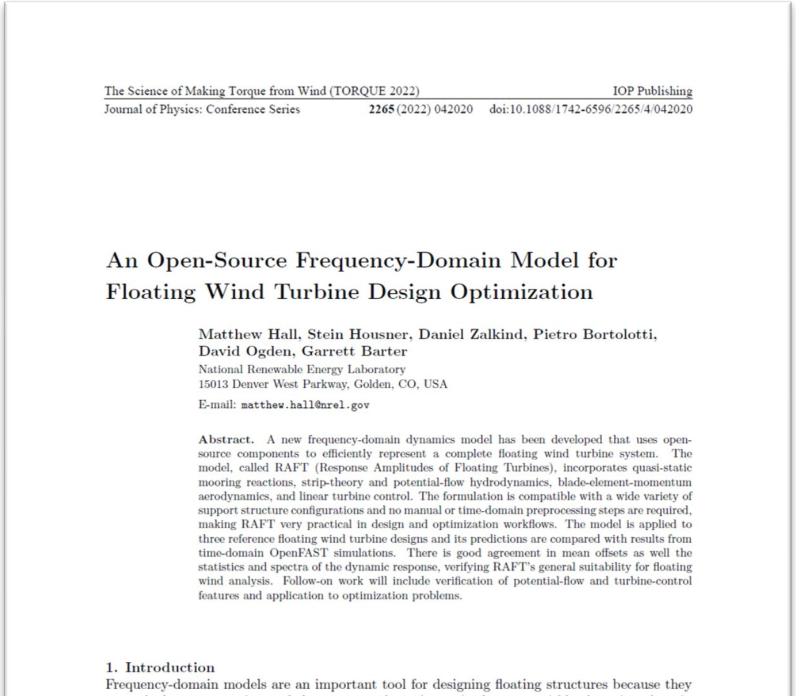
- Published 2022 by NREL
- Open-source toolbox, available on GitHub repository
- Idea: find coupled system mass, stiffness and damping for use in frequency domain
- Aerodynamic added mass and damping found from linearization



The Science of Making Torque from Wind (TORQUE 2022) IOP Publishing
Journal of Physics: Conference Series **2265** (2022) 042020 doi:10.1088/1742-6596/2265/4/042020

An Open-Source Frequency-Domain Model for Floating Wind Turbine Design Optimization

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15013 Denver West Parkway, Golden, CO, USA
E-mail: matthew.hall@nrel.gov

Abstract. A new frequency-domain dynamics model has been developed that uses open-source components to efficiently represent a complete floating wind turbine system. The model, called RAFT (Response Amplitudes of Floating Turbines), incorporates quasi-static mooring reactions, strip-theory and potential-flow hydrodynamics, blade-element-momentum aerodynamics, and linear turbine control. The formulation is compatible with a wide variety of support structure configurations and no manual or time-domain preprocessing steps are required, making RAFT very practical in design and optimization workflows. The model is applied to three reference floating wind turbine designs and its predictions are compared with results from time-domain OpenFAST simulations. There is good agreement in mean offsets as well the statistics and spectra of the dynamic response, verifying RAFT's general suitability for floating wind analysis. Follow-on work will include verification of potential-flow and turbine-control features and application to optimization problems.

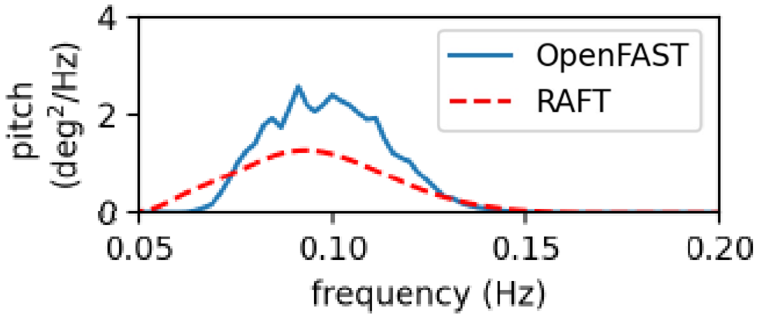
1. Introduction

Frequency-domain models are an important tool for designing floating structures because they

Source: Matthew Hall et al 2022 J. Phys.: Conf. Ser. 2265 042020

RAFT: Response Amplitudes of Floating Turbines

- Overall, good results obtained when compared to time-domain
- Mismatch in pitch and mooring tension response for semi-submersible (15MW VolturnUS-S)



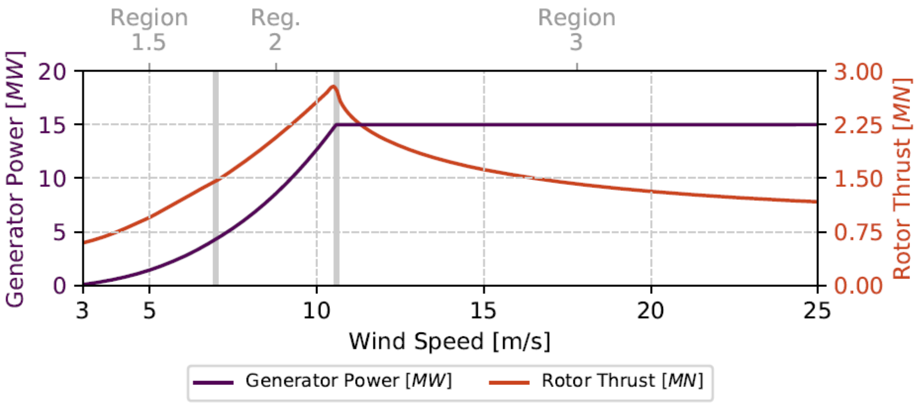
- Differences attributed to:
  - Hydrodynamic modelling (strip theory)
  - Mooring system modelling (quasi static)

- Objective: improve pitch response prediction by:
  - Improving blade pitch control implementation
  - Coupling RAFT to MARIN wave diffraction code

Image source: Matthew Hall et al 2022 J. Phys.: Conf. Ser. 2265 042020

Blade pitch control: velocity feedback

- PI controller, with setpoint on RPM
- Negative slope in thrust curve above rated wind
- Negative floater pitch damping for above-rated wind speeds
- Solution: nacelle velocity feedback
- Implemented with low-pass filter



Blade pitch actuation

Rotor speed error

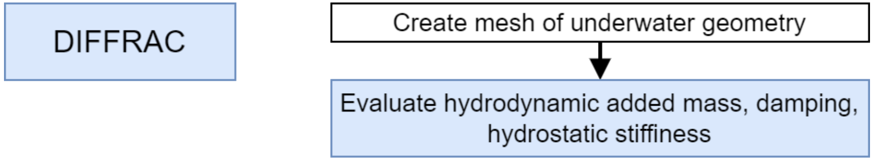
$$\Delta\beta = k_{p\beta}\Delta\Omega + k_{I\beta}\int \Delta\Omega dt + k_{px}\dot{x}$$

Proportional gain

Integral gain

Nacelle velocity

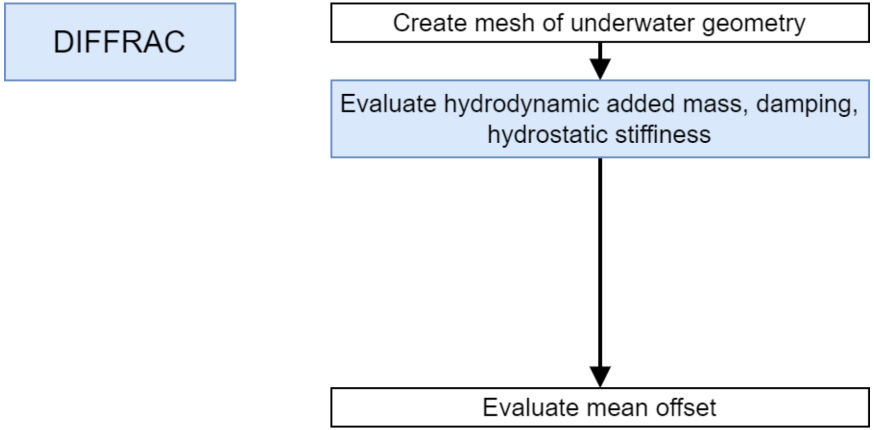
Coupling to MARIN hydrodynamic tools



Hydrodynamic look-up table (RAO)

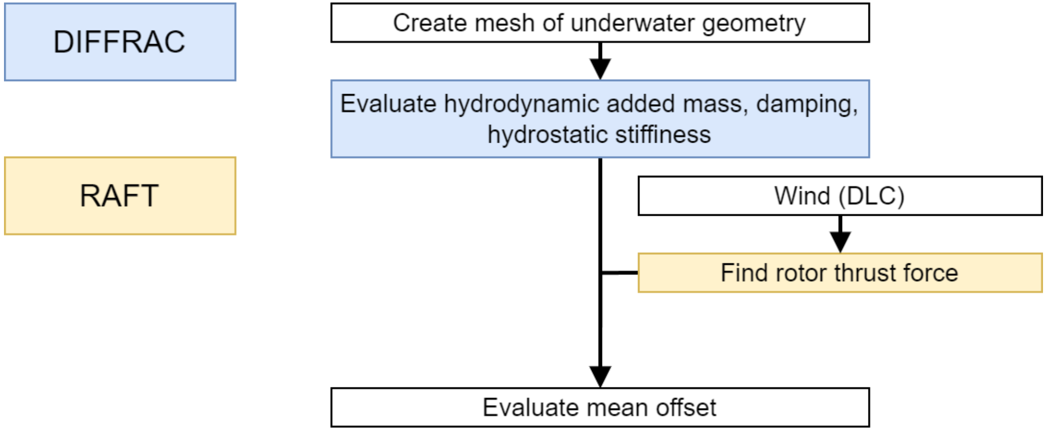
- Most expensive step
- Done for every geometry

Coupling to MARIN hydrodynamic tools



All linearization done around mean state

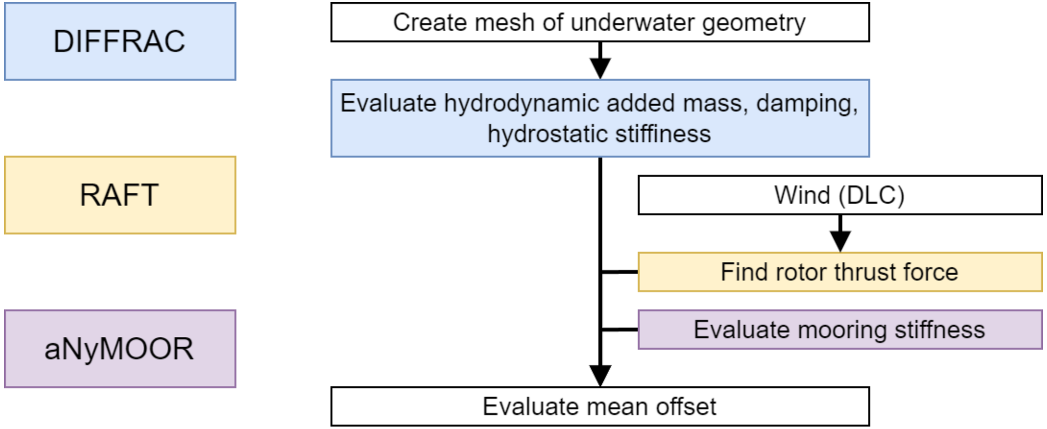
Coupling to MARIN hydrodynamic tools



Done for each:

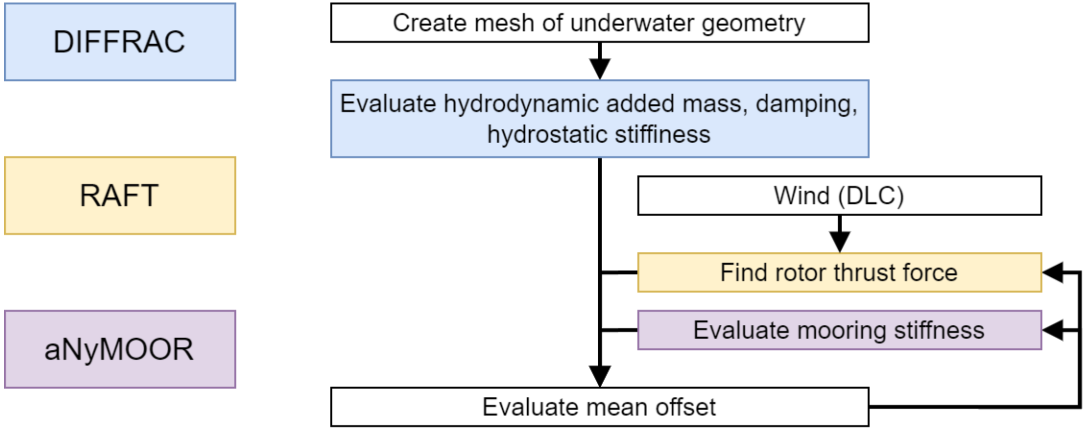
- Turbine
- Blade pitch controller
- Wind condition

Coupling to MARIN hydrodynamic tools



Static mooring system

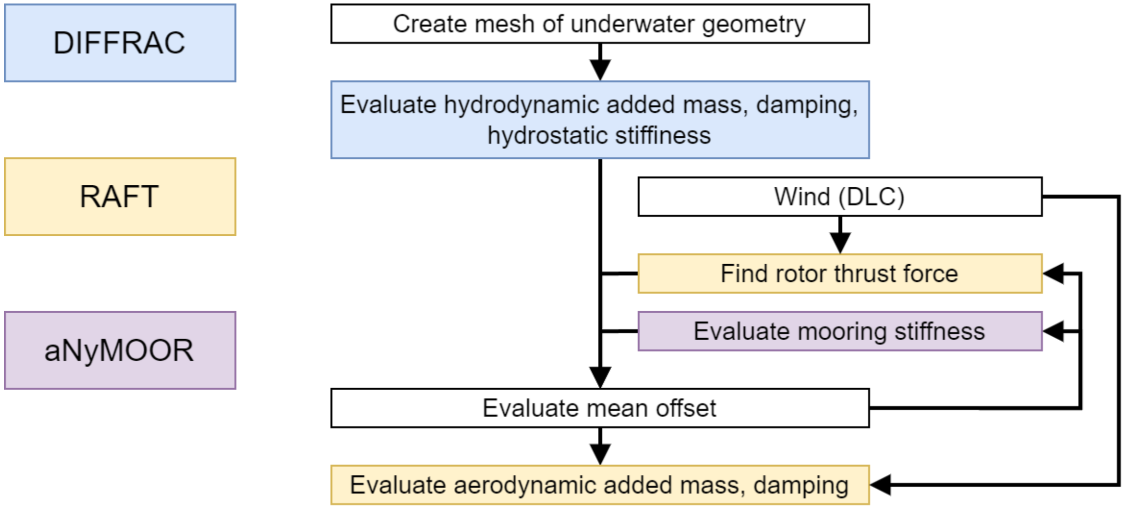
Coupling to MARIN hydrodynamic tools



Iterations needed:

- Account for rotor tilt
- Mooring stiffness linearized at offset

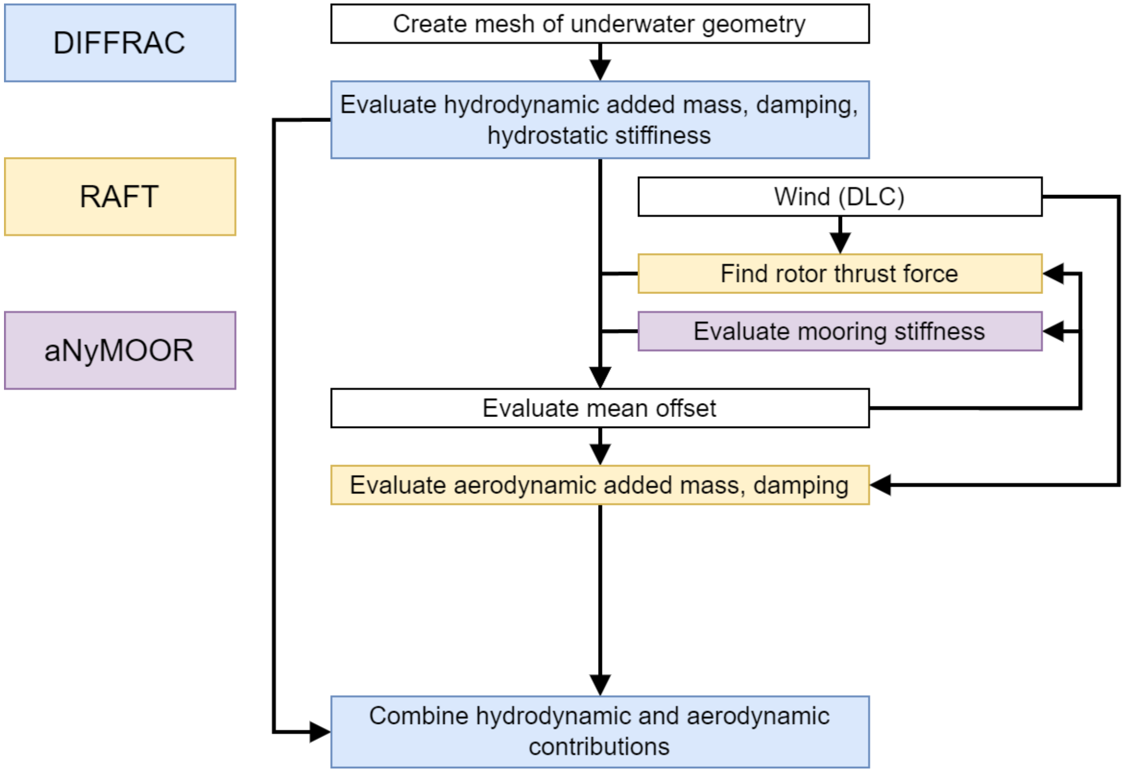
Coupling to MARIN hydrodynamic tools



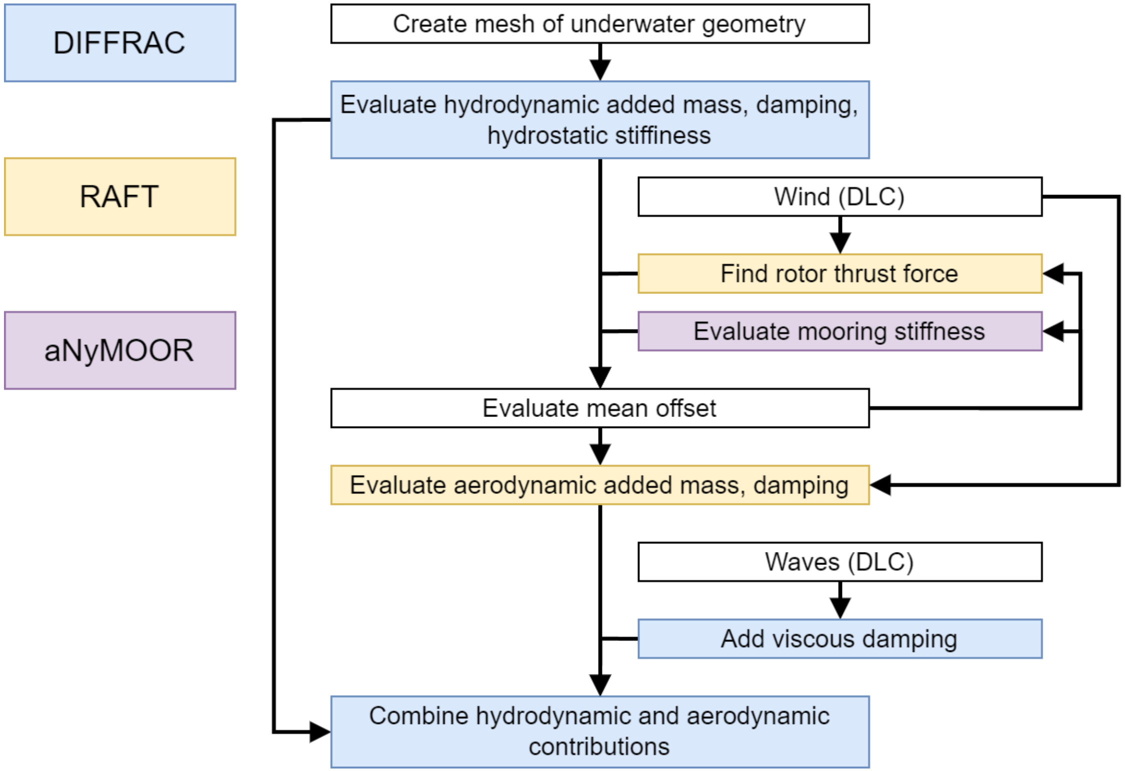
RAFT used to evaluate aerodynamic mass/damping matrices around mean

Includes blade pitch controller!

Coupling to MARIN hydrodynamic tools

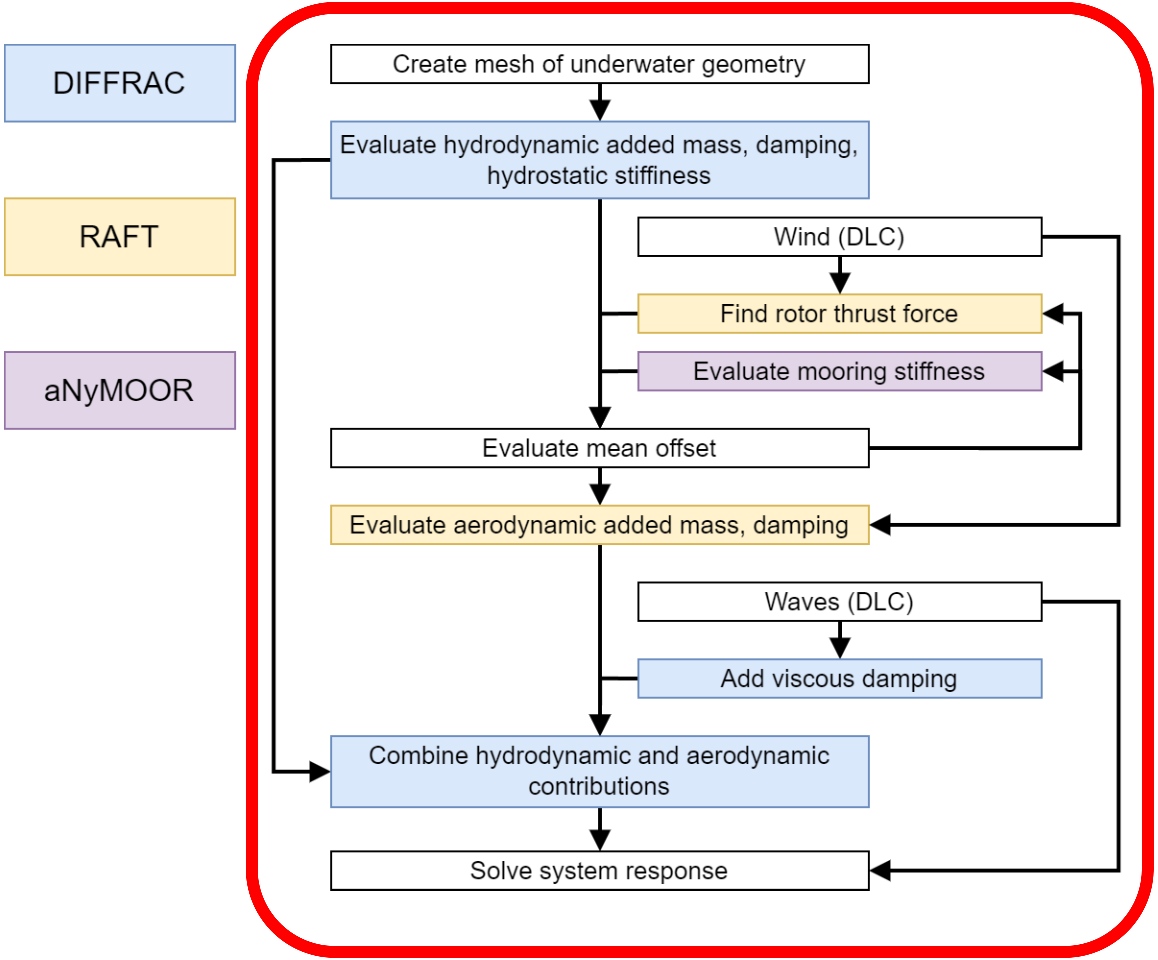


Coupling to MARIN hydrodynamic tools



Viscous damping linearized for sea state

Coupling to MARIN hydrodynamic tools



Combined system subjected to wave excitation

"RAFT extended"

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Results

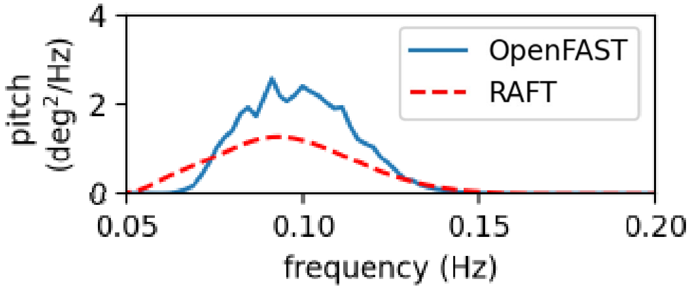
Use case

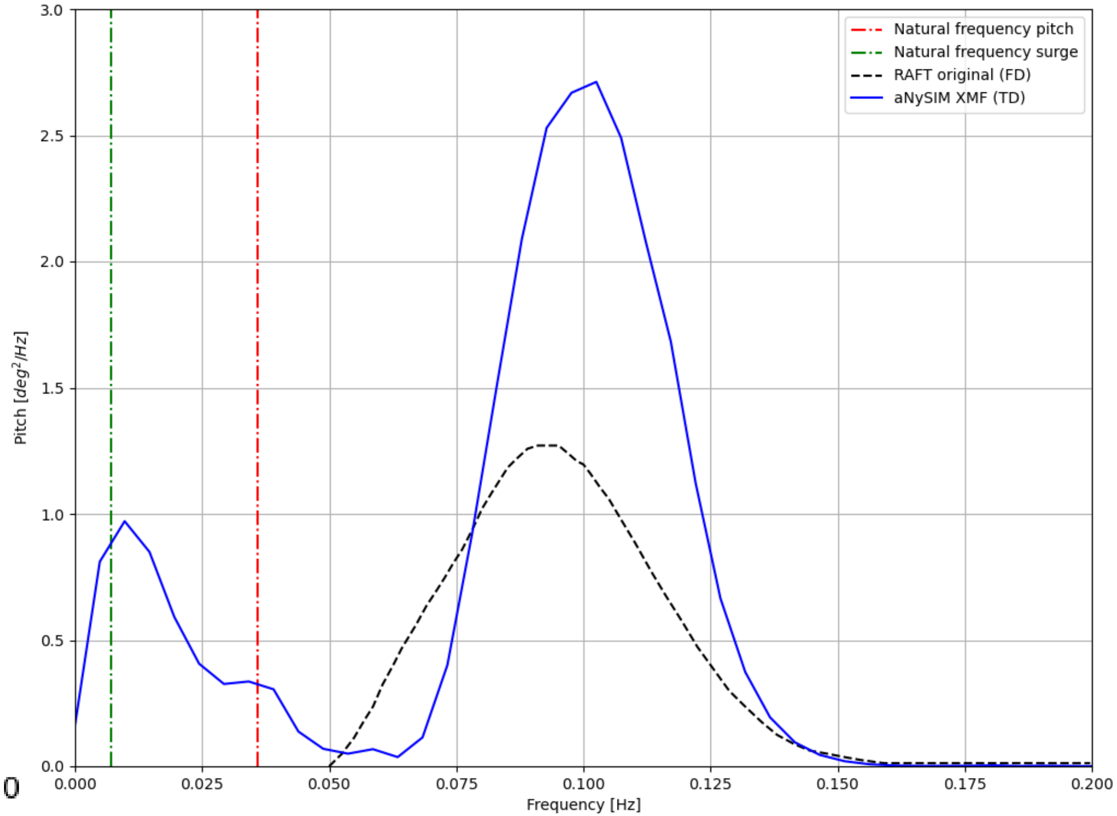
- VolturnUS-S platform
  - 15MW
  - Semi-submersible
  - Catenary mooring
- Natural frequencies
  - Surge: 0.007 Hz (142.9 s)
  - Pitch: 0.036 Hz (27.8 s)
- ROSCO controller
  - Nacelle acceleration feedback to actively dampen floater pitch motion

Source: Allen, Christopher, Anthony Viselli, Habib Dagher, Andrew Goupee, Evan Gaertner, Nikhar Abbas, Matthew Hall, and Garrett Barter. Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-76773. https://www.nrel.gov/docs/fy20osti/76773.pdf.

Wave-dominated, below-rated case

- Hs = 6.0 m
- Tp = 12.0 s
- u_{wind} = 8 m/s
- Constant wind





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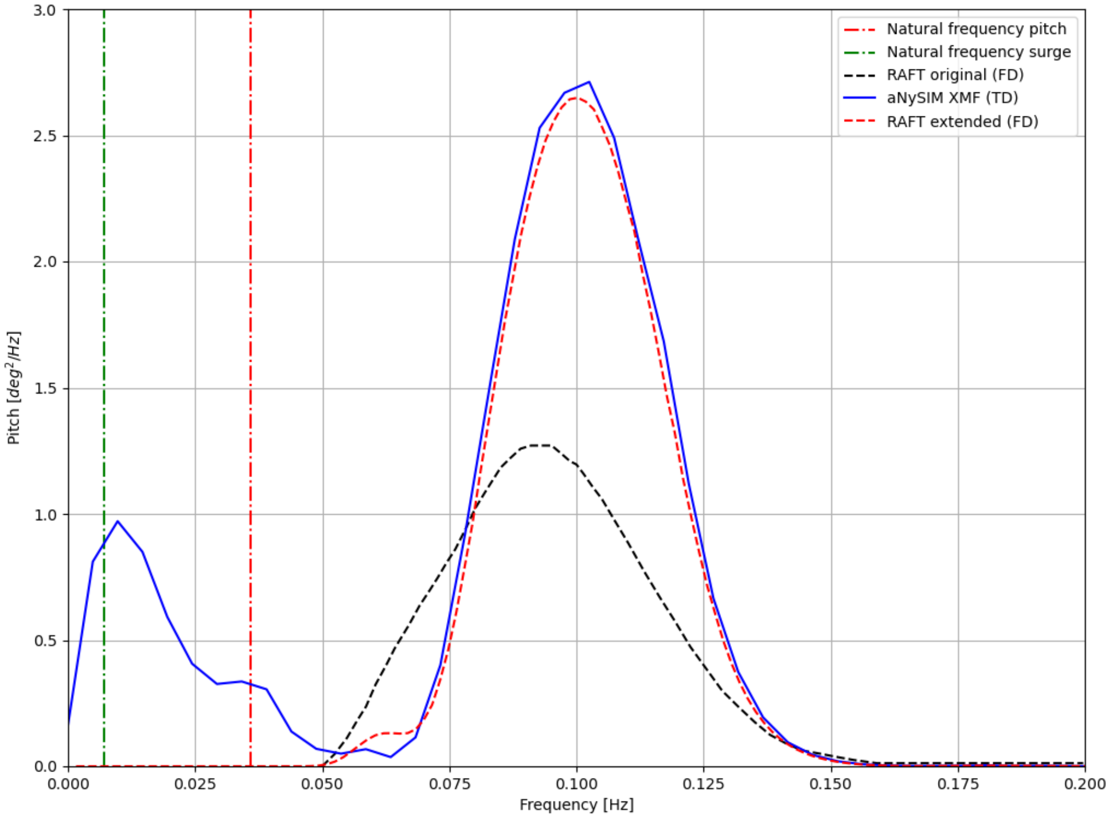

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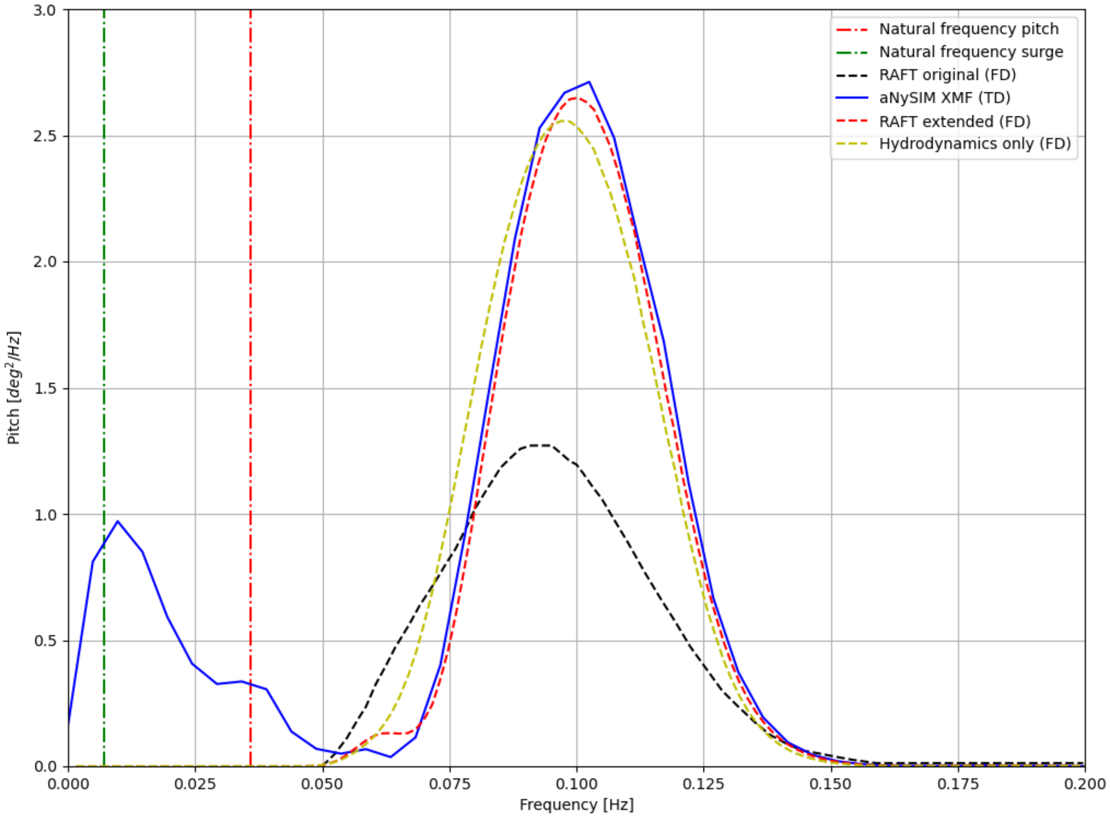
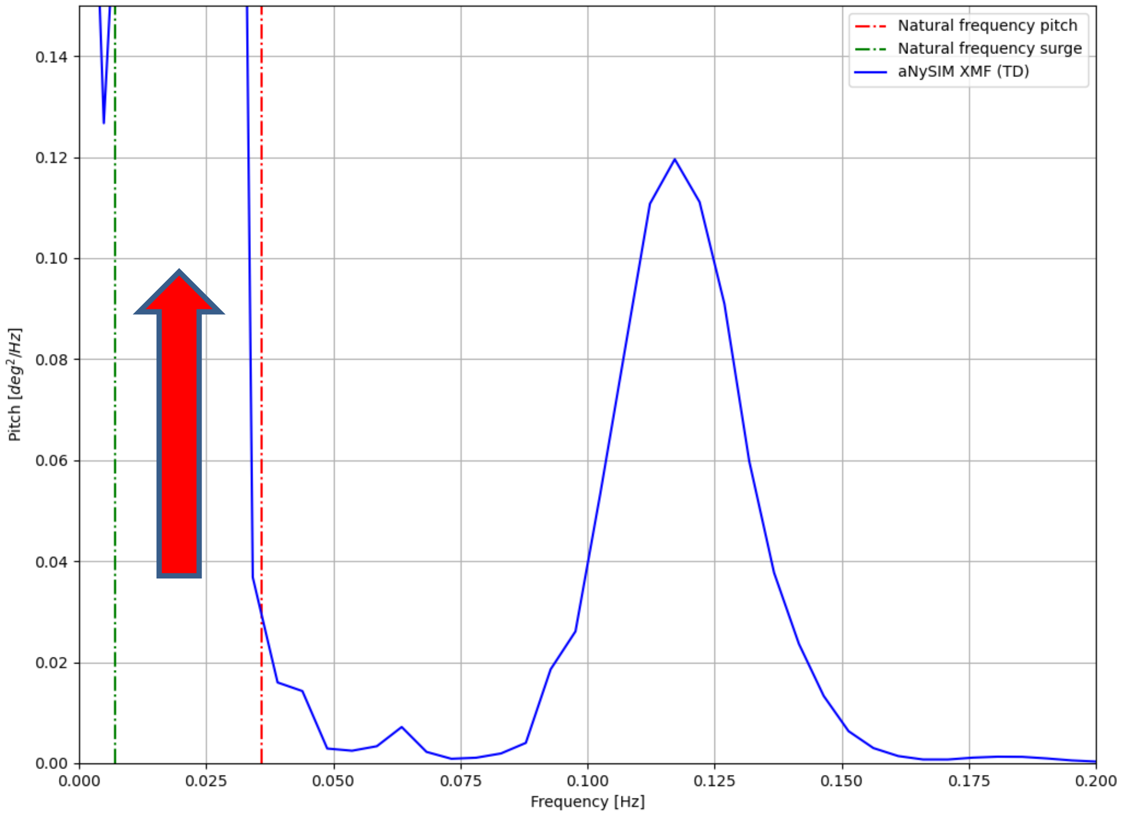


Wind-dominated, above-rated case

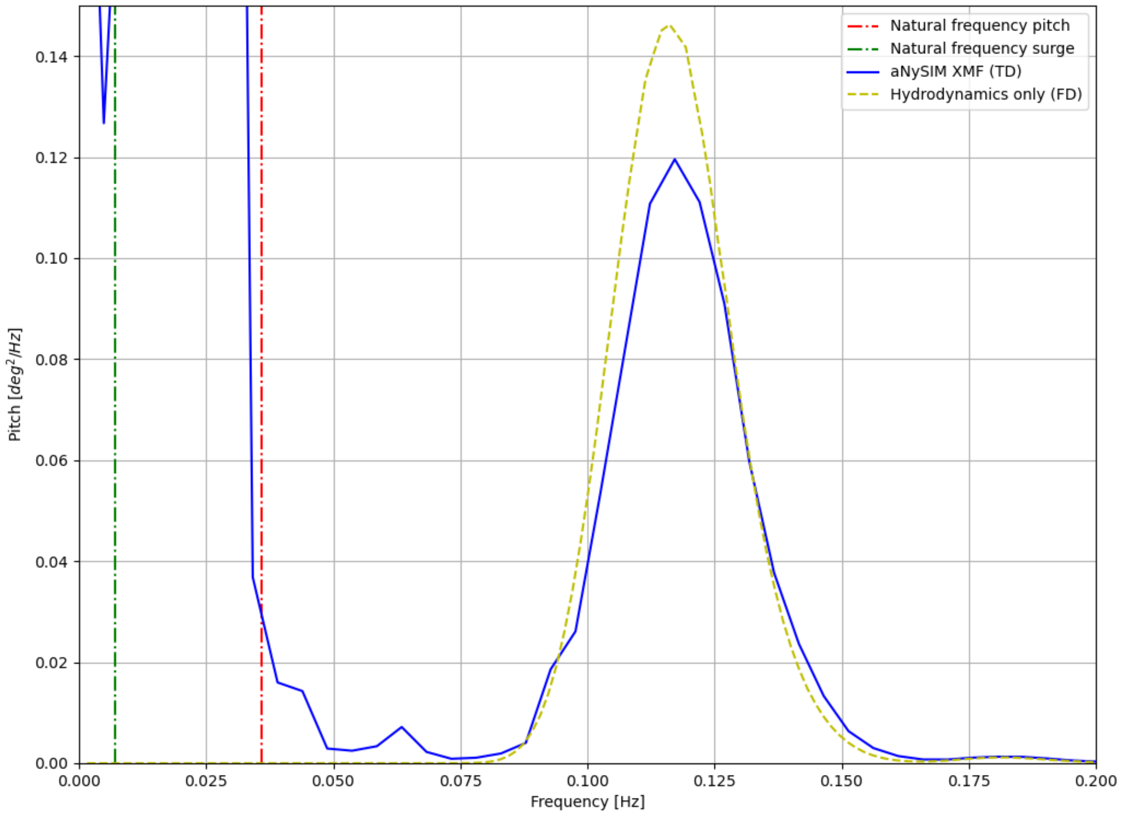
- Hs = 1.84 m
- Tp = 7.44 s
- u_{wind} = 12.0 m/s
- Steady wind

- Strong blade pitch actuation seen near natural frequencies



Wide-dominated, above-rated case

- Hs = 1.84 m
- Tp = 7.44 s
- u_{wind} = 12.0 m/s
- Steady wind



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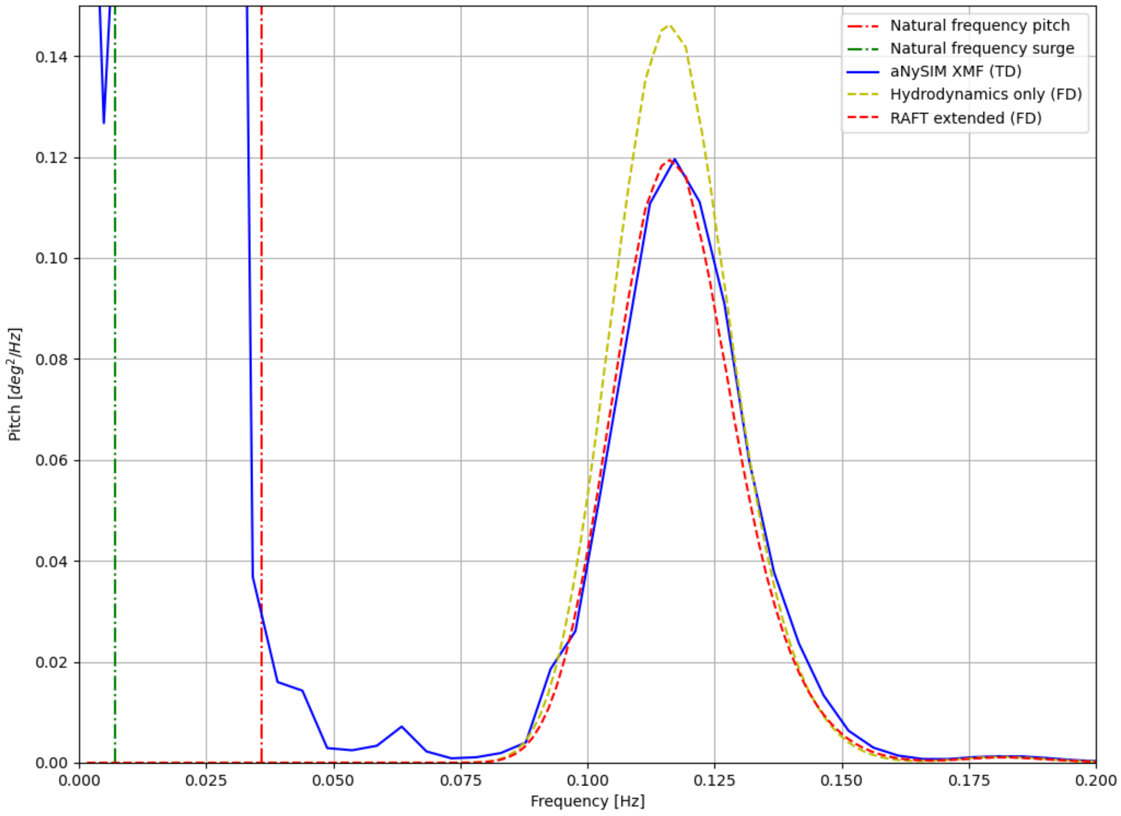
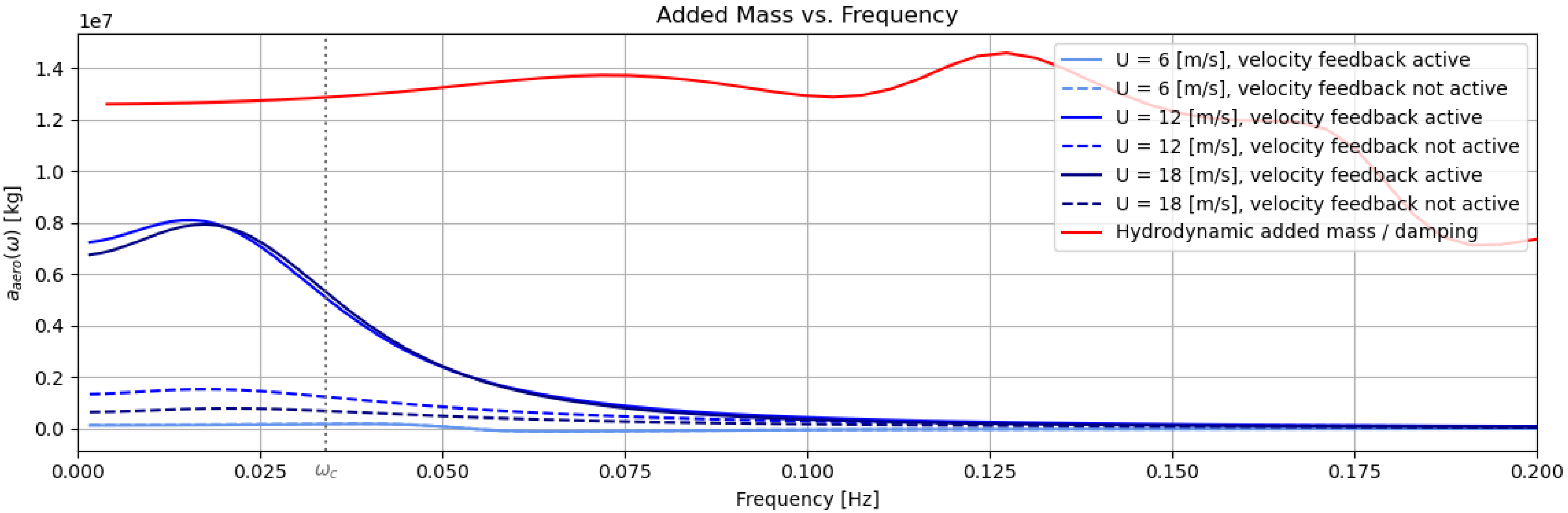


Deep dive

- So, what happens here?

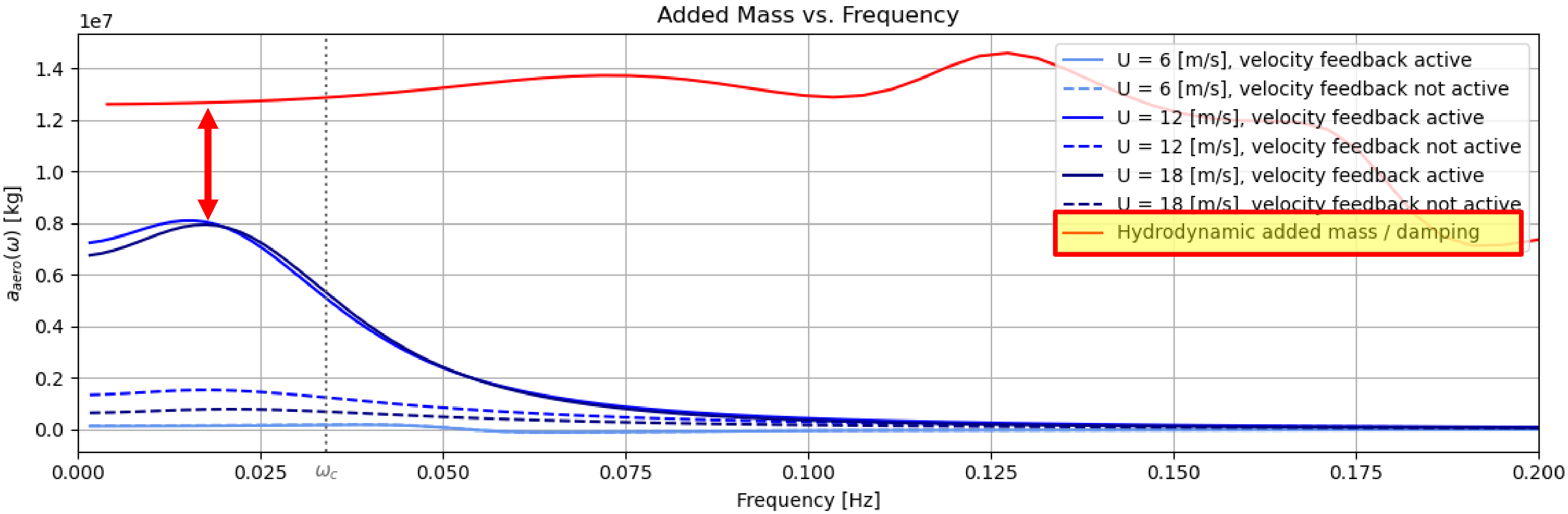
- Rotor and blade pitch controller create a response that depends on the platform motions
  - Acceleration-dependent forces: added mass
  - Velocity-dependent forces: damping

Aero-servodynamic added mass



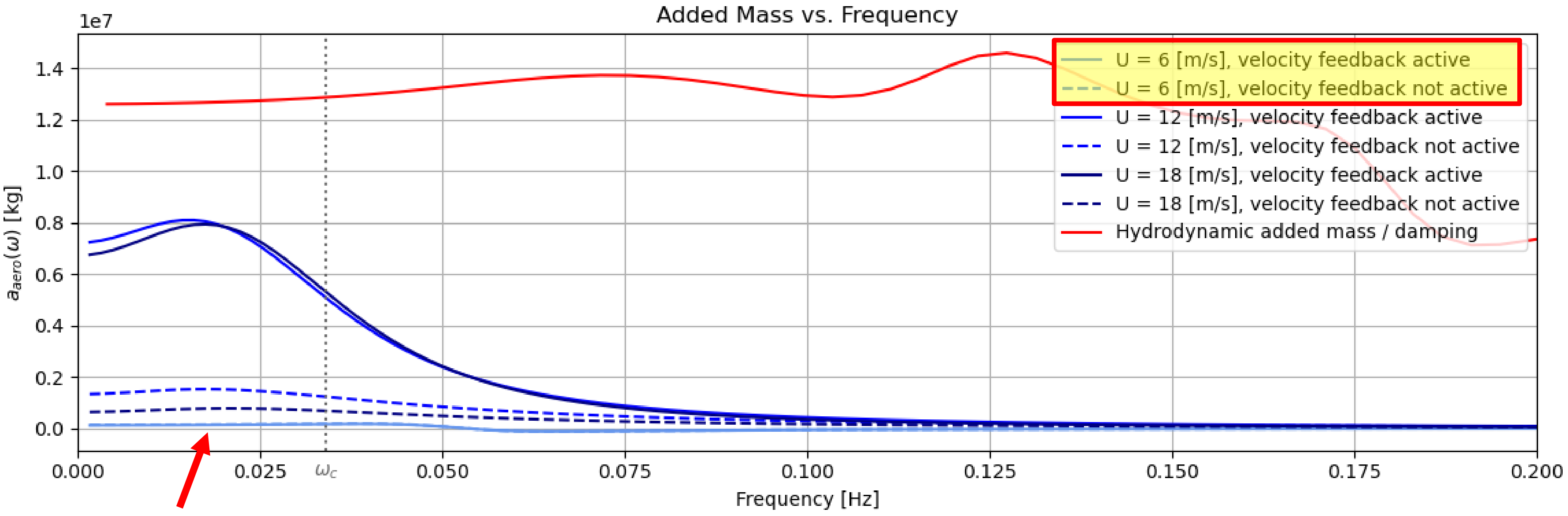
- For displacement in x-direction
- Total system mass: 2e7 kg

Aero-servodynamic added mass



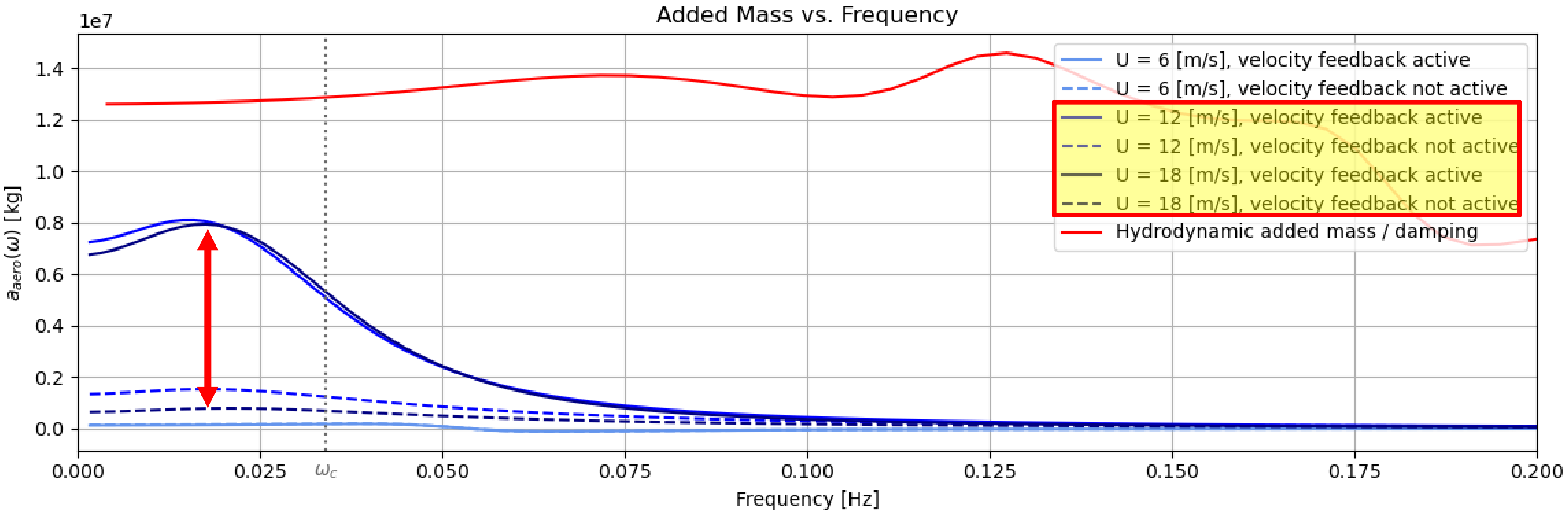
- For displacement in x-direction
- Hydrodynamic added mass dominates over aerodynamic added mass

Aero-servodynamic added mass



- For displacement in x-direction
- Below rated: small change made by controller feedback

Aero-servodynamic added mass

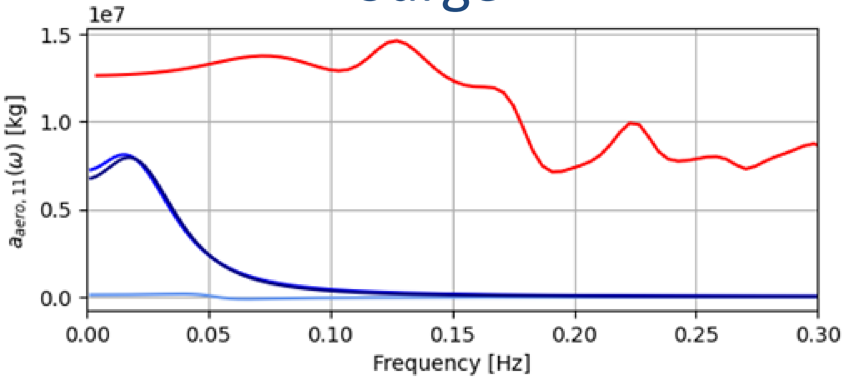


- For displacement in x-direction
- Above rated: large change made by controller feedback, strong dependence on wind speed and frequency!

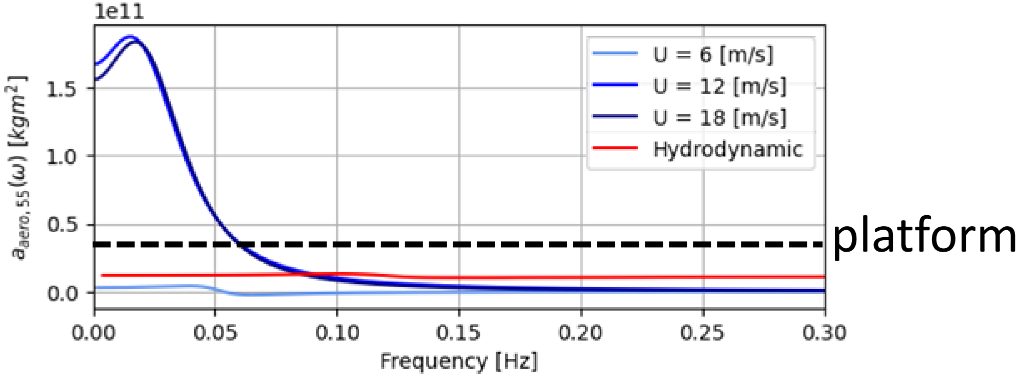
Pitch mode

- Aerodynamic effects occur at hub height: 150m
- Large effect on pitch mode due to large arm
- Platform pitch inertia: 4.2e10 $kg * m^2$

Surge



Pitch



Aero-servodynamic added mass

- Aerodynamic added mass dominant in pitch, depends on:
  - Wind speed
  - Frequency
  - Blade pitch controller strategy
- Seen in <u>system</u> natural period $\omega_n = \sqrt{k/m}$
  - Also for surge, but less extreme

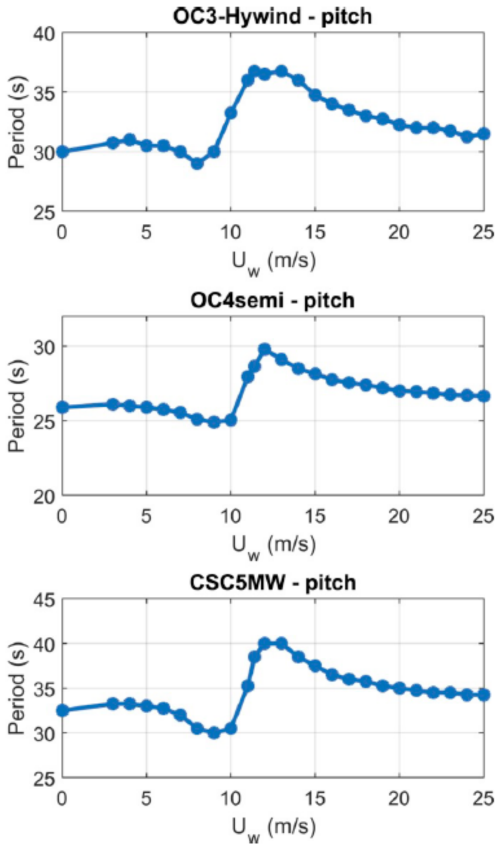
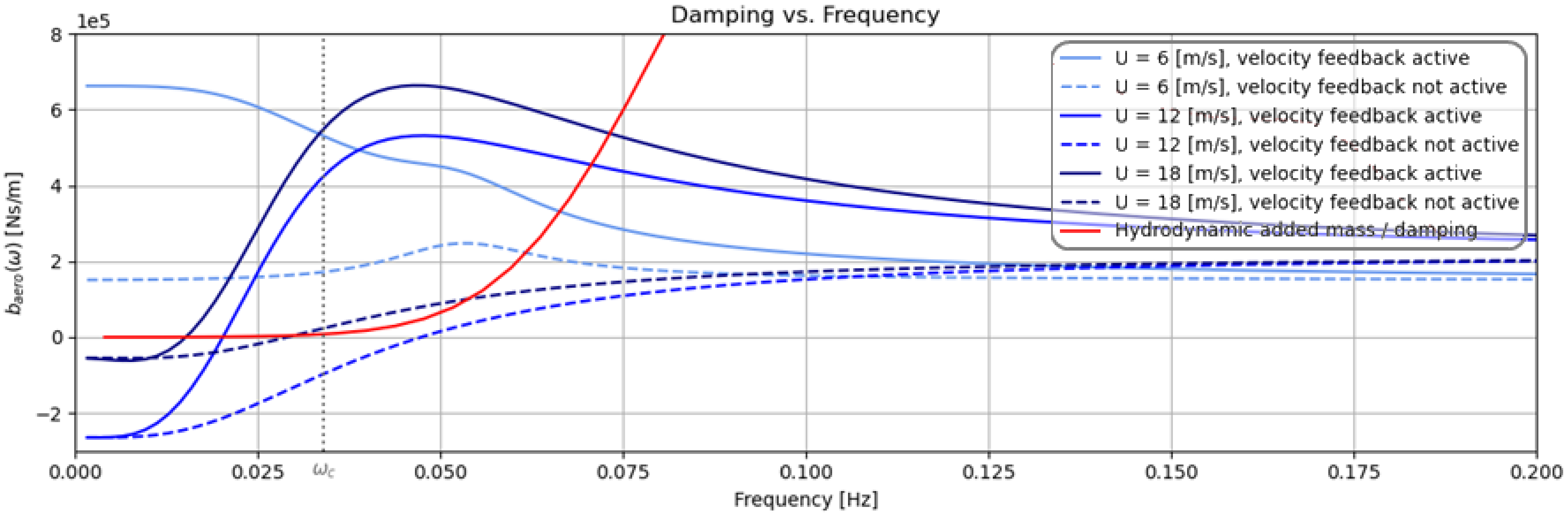


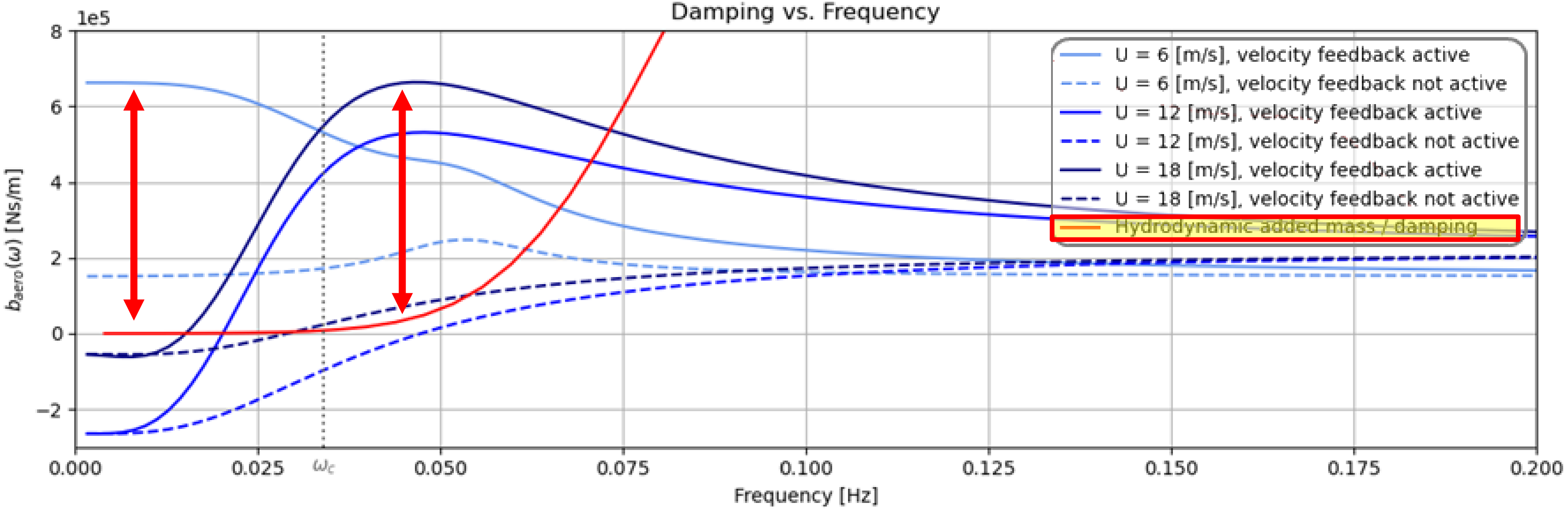
Image source: Carlos Eduardo S. Souza, Erin E. Bachynski,
Changes in surge and pitch decay periods of floating wind turbines for varying wind speed,
Ocean Engineering, Volume 180, 2019, Pages 223-237, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2019.02.075.

Aero-servodynamic damping



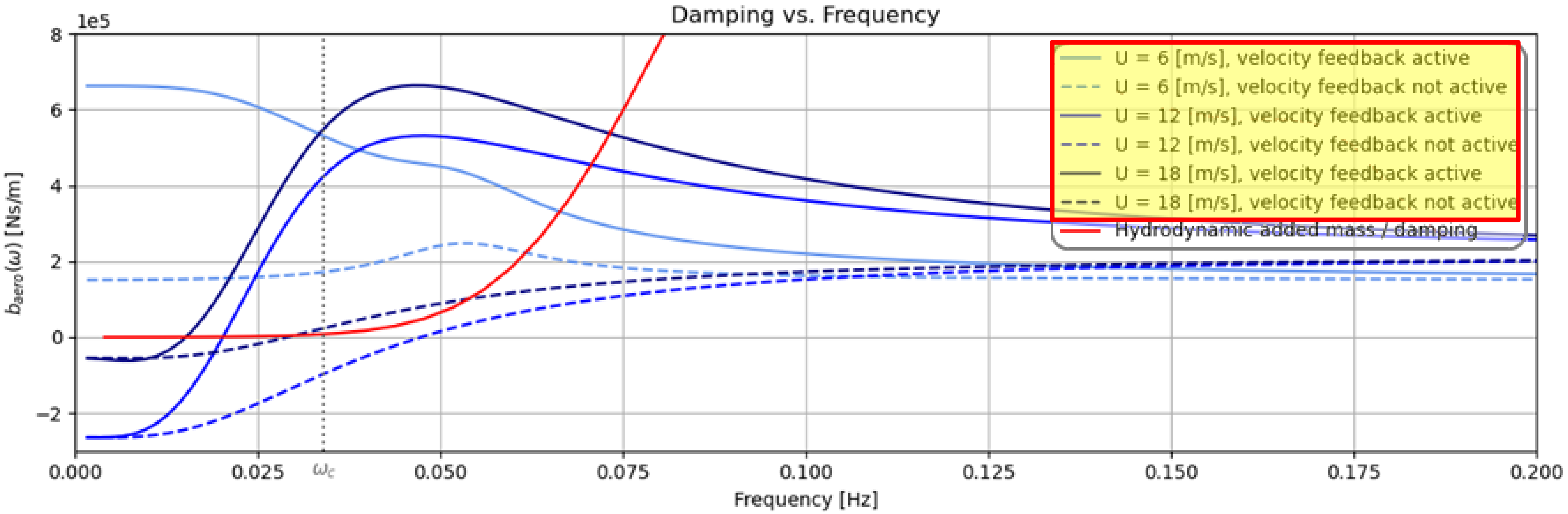
- For displacement in x-direction

Aero-servodynamic damping



- For displacement in x-direction
- Aerodynamic damping dominates over hydrodynamic damping at lower frequencies

Aero-servodynamic damping

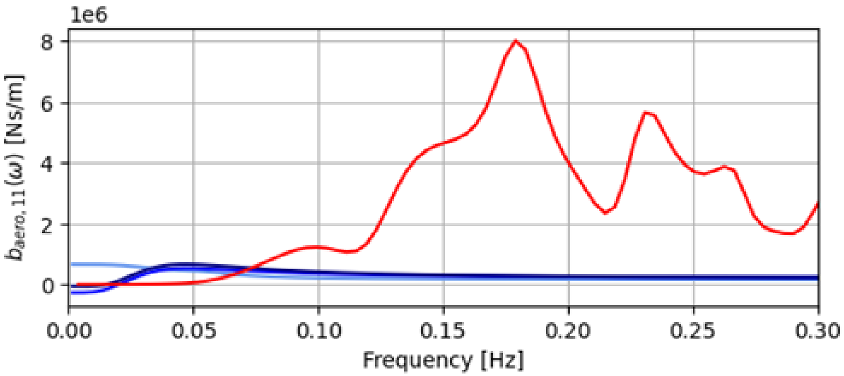


- Large dependence seen on:
  - Control strategy
  - Wind speed
  - Frequency

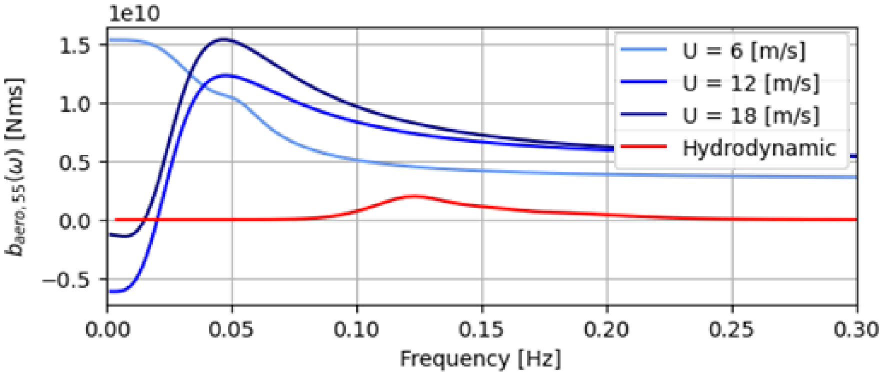
Pitch mode

- Aerodynamic effects occur at hub height: 150m
- Large effect on pitch mode due to large arm

Surge



Pitch



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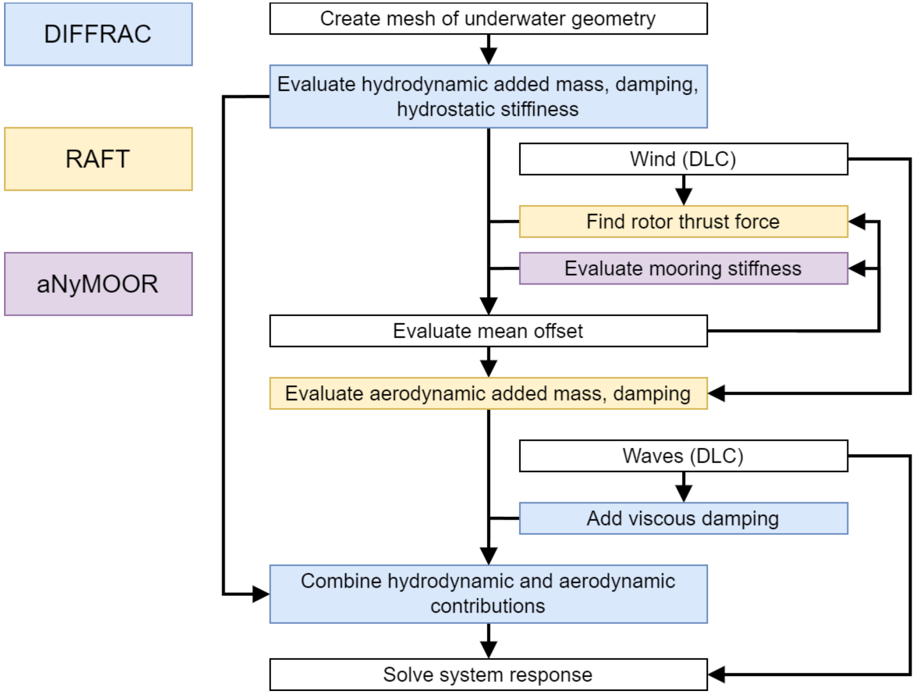
Conclusions and outlook

Conclusions

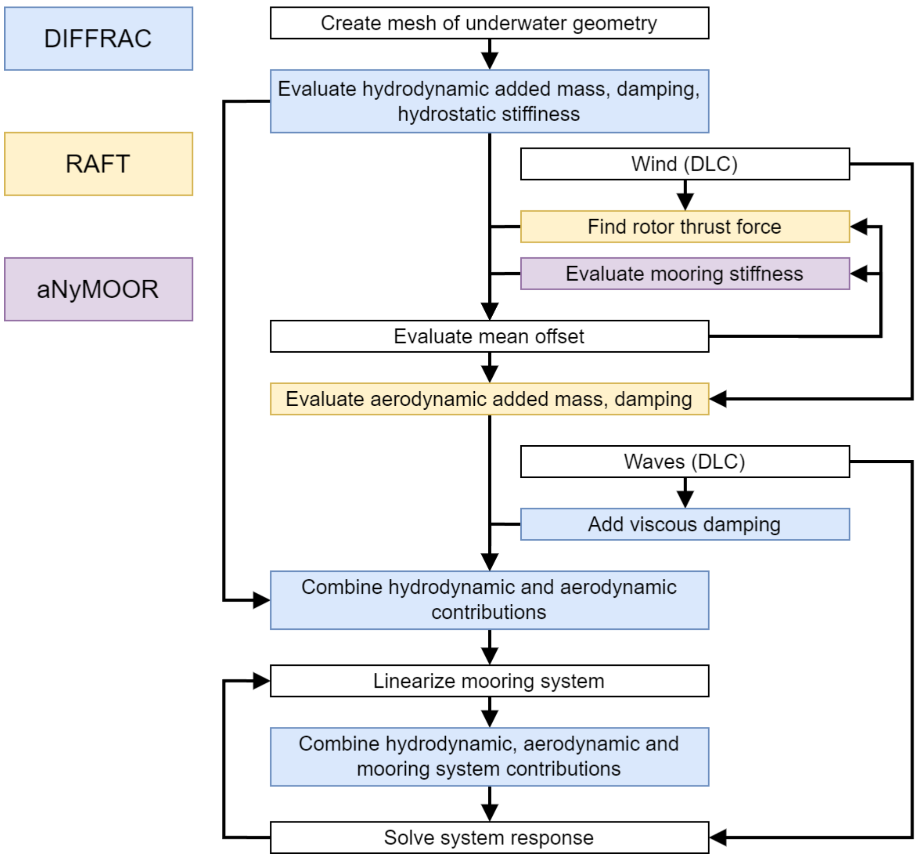
- Good match in motions in wave-frequent range
- Effects taken into account:
  - ☑ Aerodynamics
  - ☑ Hydrodynamics
  - ☐ Mooring system dynamics → Mooring line tension
  - ☐ Turbulent wind excitation → Low-frequent motions
  - ☑ Controller (PI with feedback)
  - ☐ Structural flexibility

Coupling to MARIN hydrodynamic tools



Current implementation

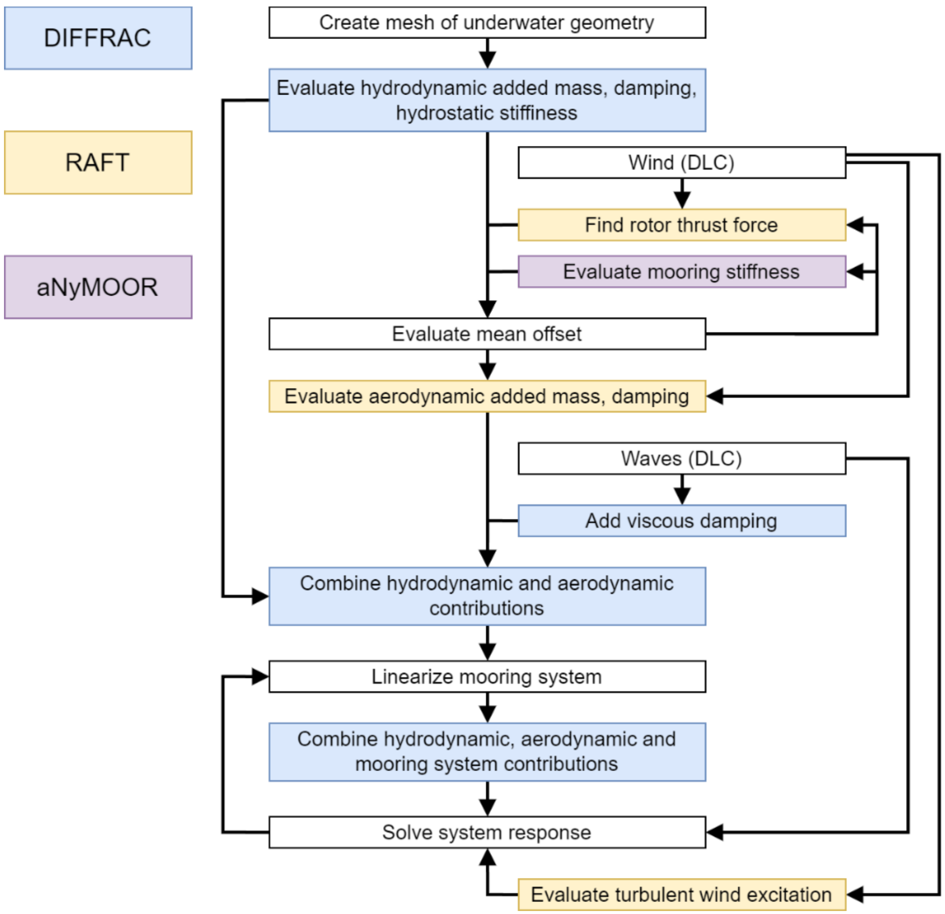
Linearizing the mooring system



Mooring line dynamics

- Linearize inertia and drag forces
- Add to (frequency-dependent) mass, stiffness, damping matrices

Adding turbulent wind excitation



Turbulent wind excitation

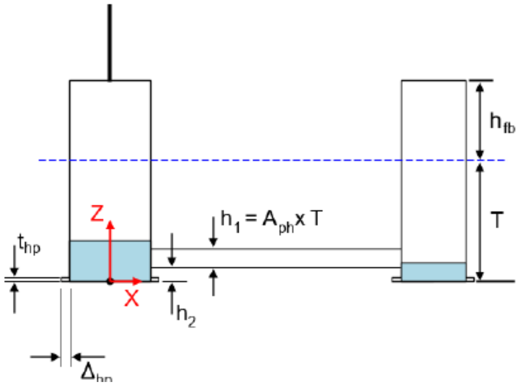
- RAFT describes transfer function H_{UF} to find the turbulent aerodynamic excitation force:

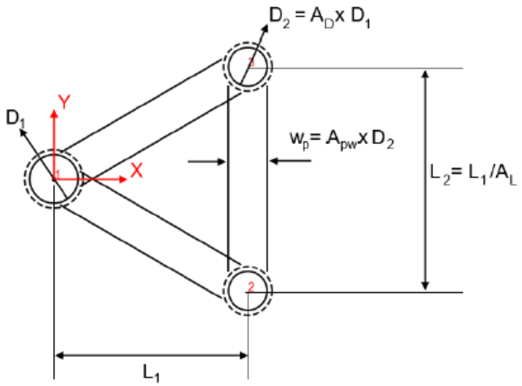
$$\hat{f}_{aero}(\omega) = H_{UF}(\omega)U(\omega)$$

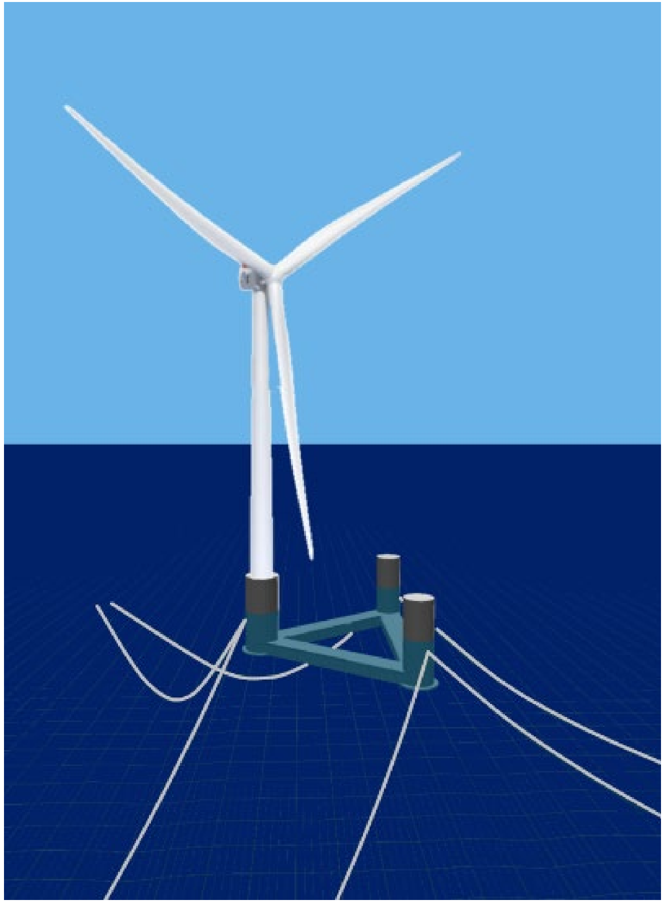
- Wind and wave spectra disconnected → superimpose
- Introduce $\hat{f}_{aero}(\omega)$ as an external, right-hand-side-force

Example: sizing of 22MW open-source reference platform

- Parametric design
- Coupled motion spectra resolved → find correct MPM platform pitch angle
- Allows to evaluate hundreds of designs in a matter of hours-days.







Outlook – application

- Resolve FOWT motions and mooring line tensions in early stage
  - Design screening
  - Optimization of floater geometry
  - Optimization of blade pitch controller
  - Response-based scaling for turbine and/or environment

- Resolve FOWT loads

- Spectra: both for ultimate (MPM) and fatigue evaluation!

- It may not be possible to linearize different control strategies

Thank you!

MARIN

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- Linearize…
  - Thrust
  - Torque
  - Rotor dynamics
  - Controller action
- Rewrite into…
  - Added mass $a_{aero}(\omega)$
  - Damping $b_{aero}(\omega)$
  - Excitation force $\hat{f}_{aero}(\omega)$

Aerodynamic linearization - thrust

$$T = \bar{T} + T_U \Delta(U - \dot{x}) + T_\Omega \Delta\Omega + T_\beta \Delta\beta$$

Aerodynamic linearization - thrust

$$T = \bar{T} + T_U \Delta(U - \dot{x}) + T_\Omega \Delta\Omega + T_\beta \Delta\beta$$

Mean thrust

Aerodynamic linearization - thrust

$$T = \bar{T} + T_U \Delta(U - \dot{x}) + T_\Omega \Delta\Omega + T_\beta \Delta\beta$$

How do the wind speed and nacelle motion affect the thrust?

Mean thrust

Aerodynamic linearization - thrust

$$T = \bar{T} + T_U \Delta(U - \dot{x}) + T_\Omega \Delta\Omega + T_\beta \Delta\beta$$

How does the rotor speed affect the thrust?

How do the wind speed and nacelle motion affect the thrust?

Mean thrust

Aerodynamic linearization - thrust

$$T = \bar{T} + T_U \Delta(U - \dot{x}) + T_\Omega \Delta\Omega + T_\beta \Delta\beta$$

How does the blade pitch angle affect the thrust?

How does the rotor speed affect the thrust?

How do the wind speed and nacelle motion affect the thrust?

Mean thrust

Most probably maximum (MPM)

Zeroth and second moment of response spectrum:

$$m_0 = \int S_w(\omega) * RAO(\omega)^2 d\omega$$

$$m_2 = \int S_w(\omega) * RAO(\omega)^2 * \omega^2 d\omega$$

Zero crossing period:

$$T_Z = 2\pi\sqrt{m_0/m_2}$$

Root-mean-square of response:

$$RMS = \sqrt{m_0}$$

Most probable maximum:

$$MPM = \sqrt{2 \ln N} * RMS$$
$$N = T_{eval}/T_z$$