Floating Substructures & Moorings

for Floating Offshore Wind Turbines

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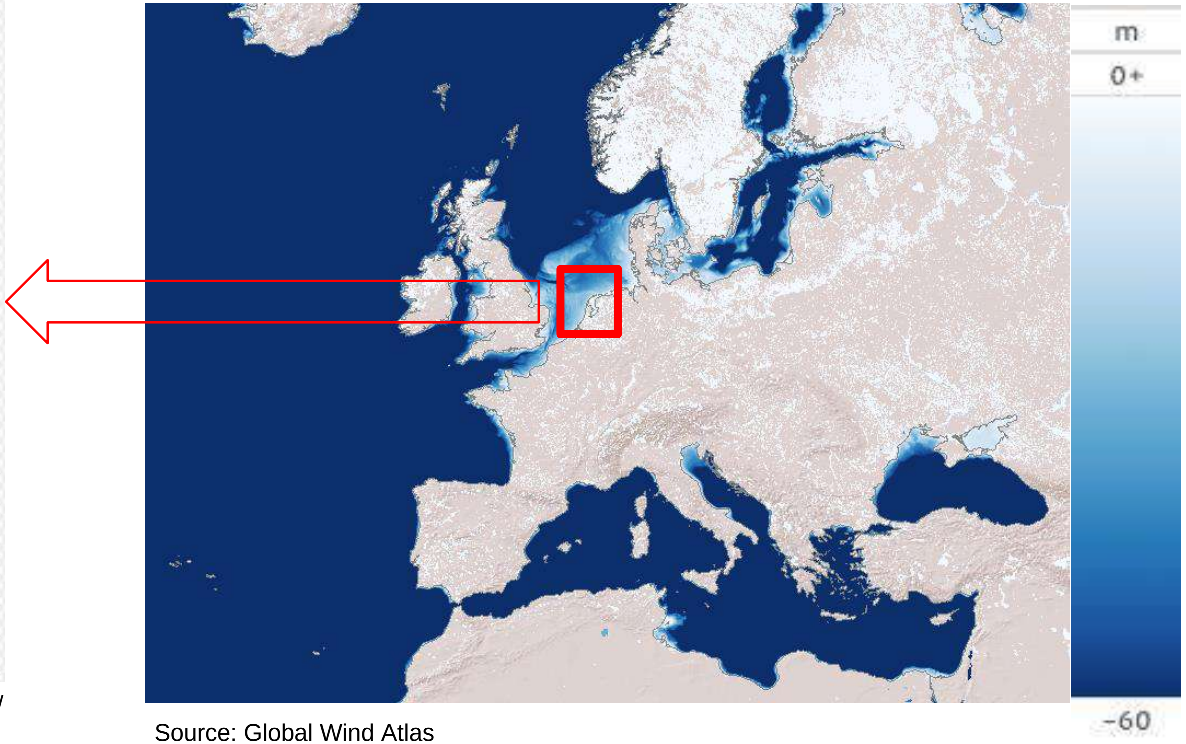
Motivation for Floating Offshore Wind

- Better resource potential for offshore wind
- Space for bottom-founded OWT becomes scarce

Ample space?

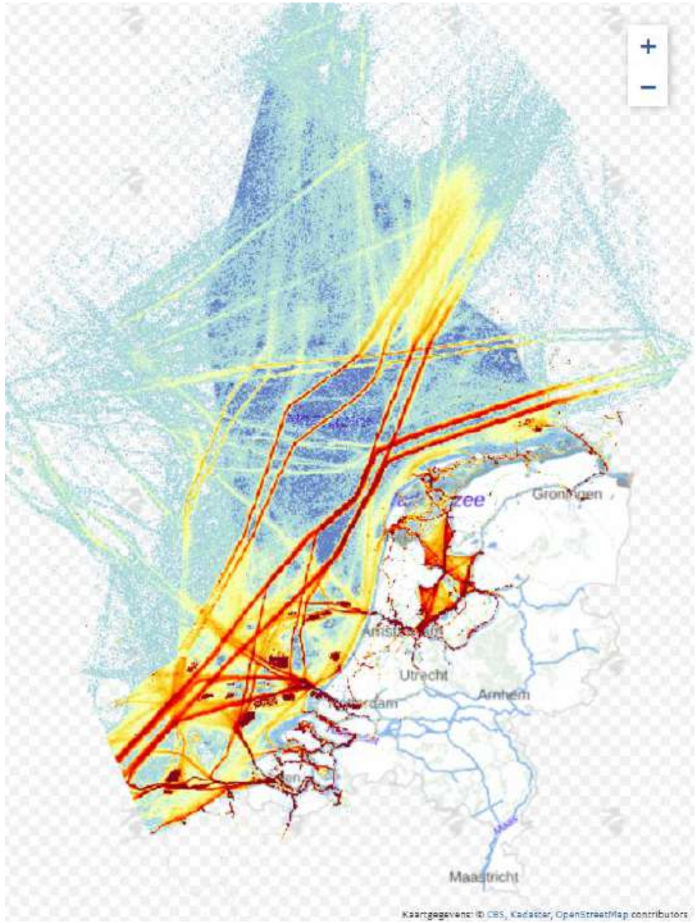
https://www.noordzeeloket.nl/en/up-date-atlas/



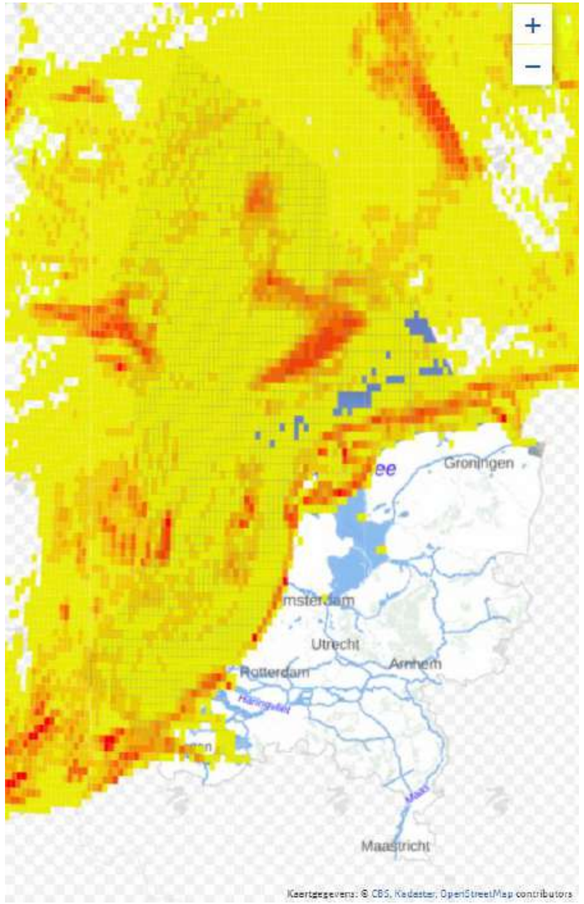
Source: Global Wind Atlas

Usage of the North Sea

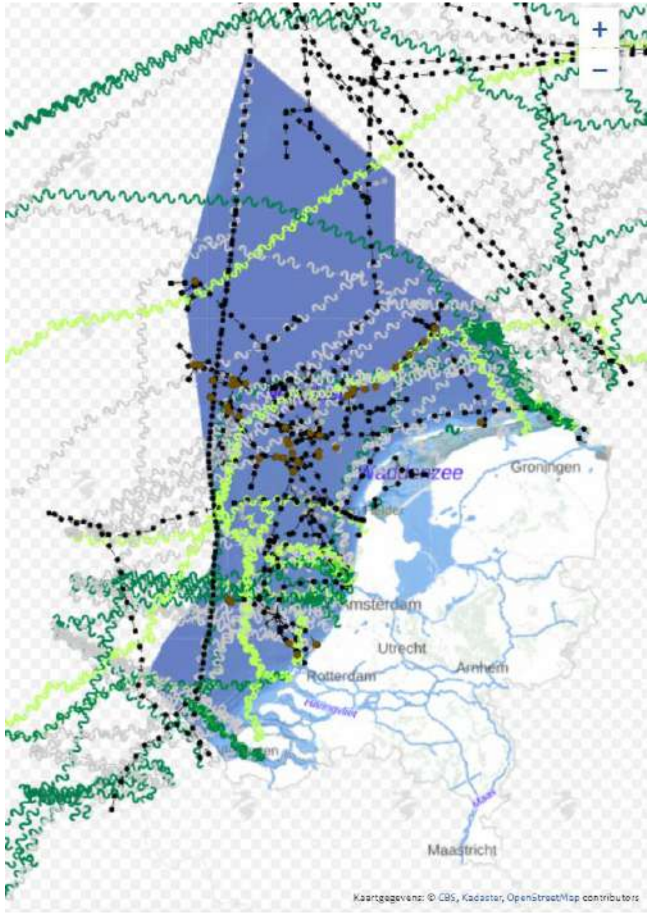
Shipping intensity



Fishing intensity



Cables & Pipelines



https://www.noordzeeloket.nl/en/up-date-atlas/#canvas

Most Waters are Deeper than 60 m!

Source: Global Wind Atlas

How to go Floating?

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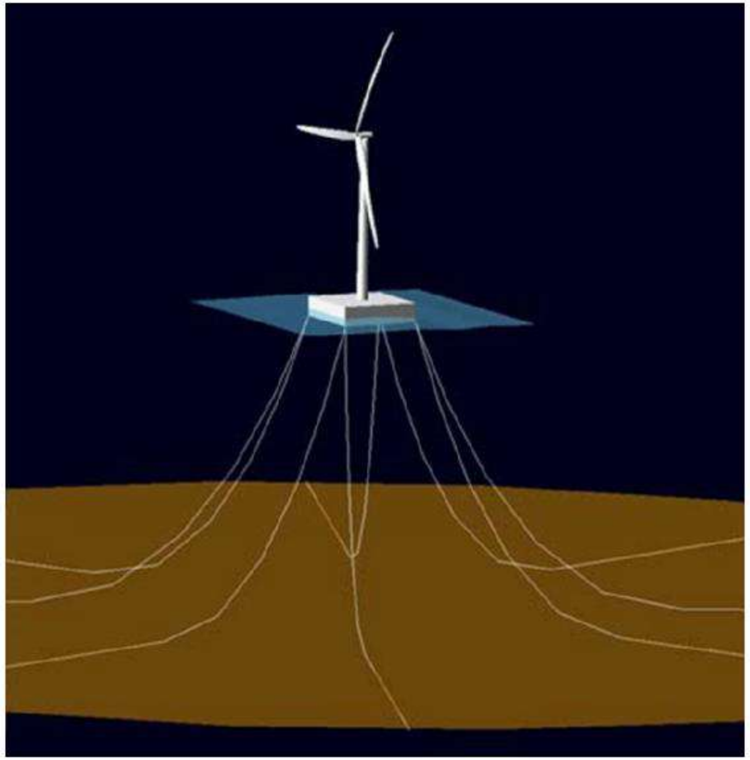

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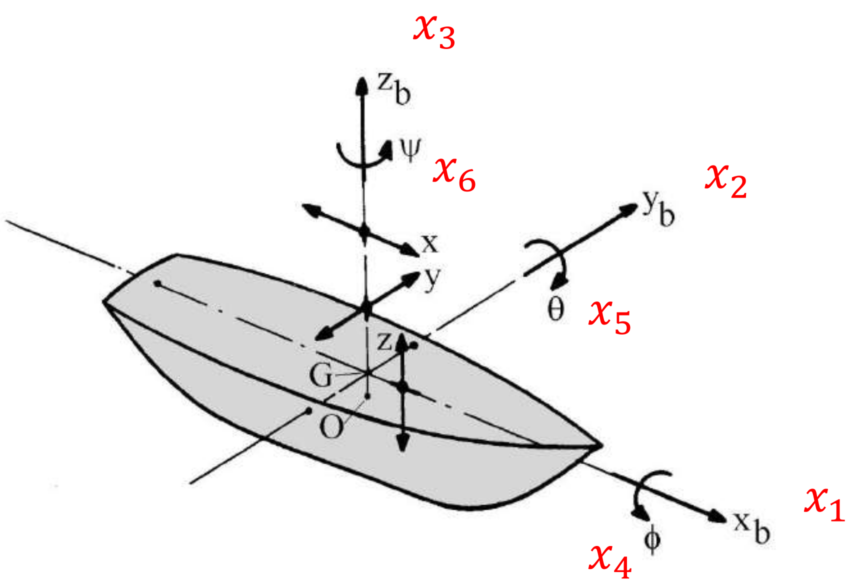
Reference Sheet Floater Motions

Index	Motion name	Common symbol	x_i-Notation
1	Surge	x	x_1
2	Sway	y	x_2
3	Heave	z	x_3
4	Roll	φ	x_4
5	Pitch	Θ	x_5
6	Yaw	ψ	x_6



Motions and Loading 3D Floater

- Mass-Spring-Damper system: RAO → Connection of excitation and response
- $m\,\ddot{z} + b\,\dot{z} + c\,z = F_a e^{-i\omega t}$ $\qquad z = z_a e^{-i(\omega t + \epsilon)}$

$$\frac{z_a}{F_a} = \frac{1}{\sqrt{(c - m\omega^2)^2 + b^2\omega^2}} \qquad \frac{z_a}{F_a} \rightarrow RAO \qquad \epsilon = \operatorname{atan}\left(\frac{-b\omega}{c - m\omega^2}\right)$$

$F_a = F(\zeta_a)$ $\quad m \rightarrow m + a$ $\quad \zeta_a$ $\quad m \rightarrow m + a$

- 6 dof equation of motion

$$\begin{bmatrix} M+a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & M+a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & M+a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & I_{xx}+a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & I_{yy}+a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & I_{zz}+a_{66} \end{bmatrix} \cdot \begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\varphi} \\ \ddot{\theta} \\ \ddot{\psi} \end{pmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} & b_{16} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} & b_{26} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} & b_{36} \\ b_{41} & b_{42} & b_{43} & b_{44} & b_{45} & b_{46} \\ b_{51} & b_{52} & b_{53} & b_{54} & b_{55} & b_{56} \\ b_{61} & b_{62} & b_{63} & b_{64} & b_{65} & b_{66} \end{bmatrix} \cdot \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} + \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66} \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ \varphi \\ \theta \\ \psi \end{pmatrix} = \begin{pmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{pmatrix}$$

see note

→ RAOs and phase angles of floater motion

Note: In this course, mass moment of inertia is expressed as J to avoid confusion with area moment of inertia (commonly I)

Challenges of Floating Offshore Wind Turbines

- Buoyancy
- Stability
- Wave-induced motions (of the complete aero-servo-elasto-**hydrodynamic** system)
- Station keeping
- Installation
- Energy export, i.e. dynamic cables (not covered in this lecture)

Buoyancy

Basic Archimedes

- $F_B = F_G$
- $F_B = \rho g \nabla$
- ∇ - displaced water volume, i.e. displacement
- F_G - weight of the structure

Stability

- In floating structures terms
  The capability of a floating structure to resist an inclining moment

Righting Moment

- Wind force F_w → inclining moment $M_k = F_w \cdot H_{hub} \cdot \cos\theta$
- Pitch angle $\theta > 0$ from equilibrium at $\theta = 0$
- Geometry change of displaced water volume
- Center of Buoyancy moves from B_0 to B
- New working line of buoyancy force F_B
- Weight F_G and buoancy F_B equally large and opposite
- F_B and F_G in parallel with distance $\overline{GZ}$

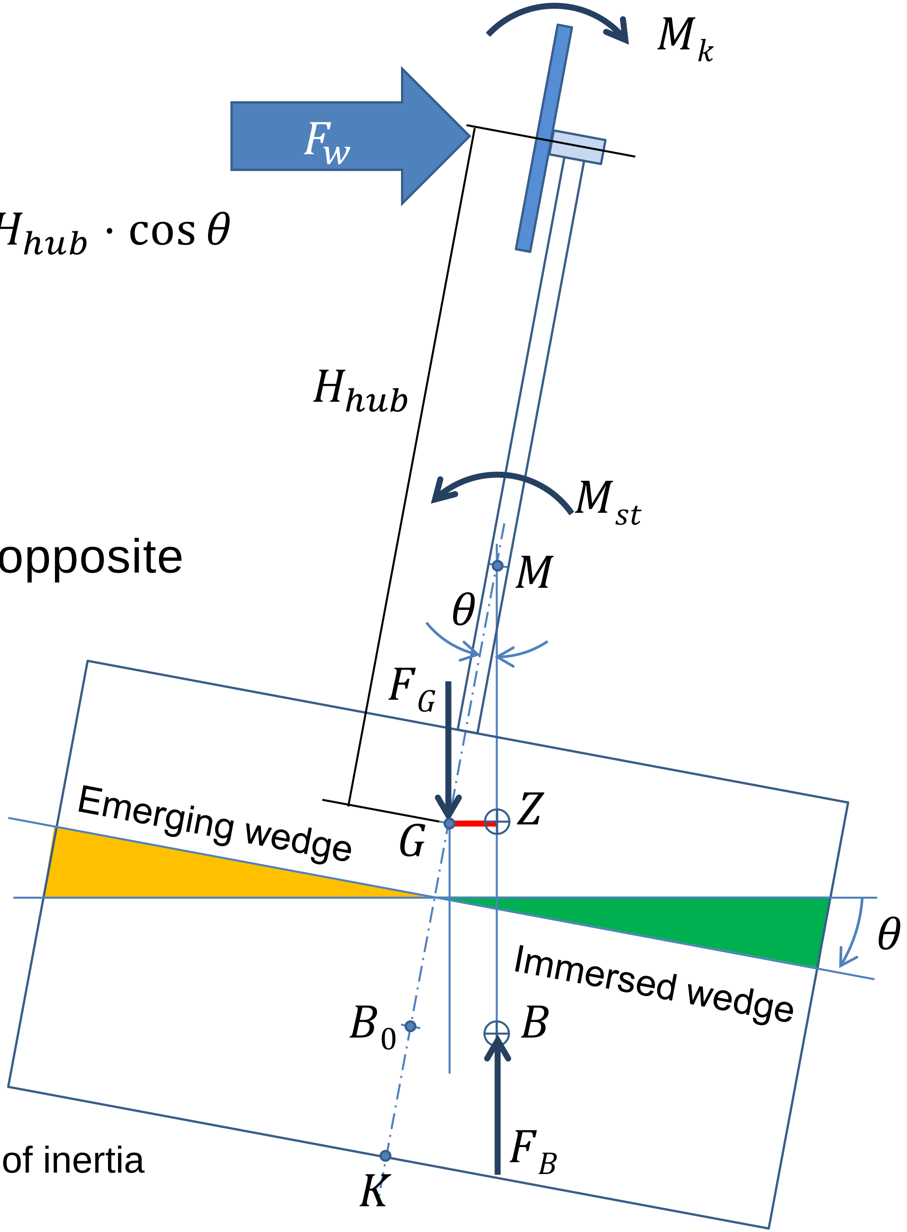
→ Righting moment M_{st}

$$M_{st} = \rho g \nabla \cdot \overline{GZ} \qquad M_{st} = M_k$$

Righting arm $\overline{GZ} = \overline{GM} \cdot \sin\theta$

Metacentric height $\overline{GM} = \overline{KB} + \overline{BM} - \overline{KG}$

Metacentric radius $\overline{BM} = \dfrac{I_{wp}}{\nabla}$



I_{wp} - area moment of inertia of waterplane area

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Hydrostatic Stiffness

- Stiffness: Change of restoring force related to corresponding displacement $c_x = \frac{dF_x}{dx}$

- Pitch righting moment $M_{st} = \rho g \nabla \cdot \overline{GZ} = \rho g \nabla \cdot \overline{GM} \sin\theta$
- $c_\theta = c_{55} = \frac{dM_{st}}{d\theta} = \rho g \nabla \cdot \overline{GM} \cos\theta \approx \rho g \nabla \cdot \overline{GM}$ for small angles

- Heave restoring force
- Change in buoyancy due to heave motion
- $c_z = c_{33} = \frac{dF_B}{dz} = \rho g \frac{d}{dz}(\nabla_0 + A_{wl} \cdot z) = \rho g A_{wl}$

A_wl – waterplane area

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Natural Frequencies of Floating Bodies

- $\omega_n = \sqrt{\frac{c}{m}}$

  c – stiffness
  m – mass (inertia)

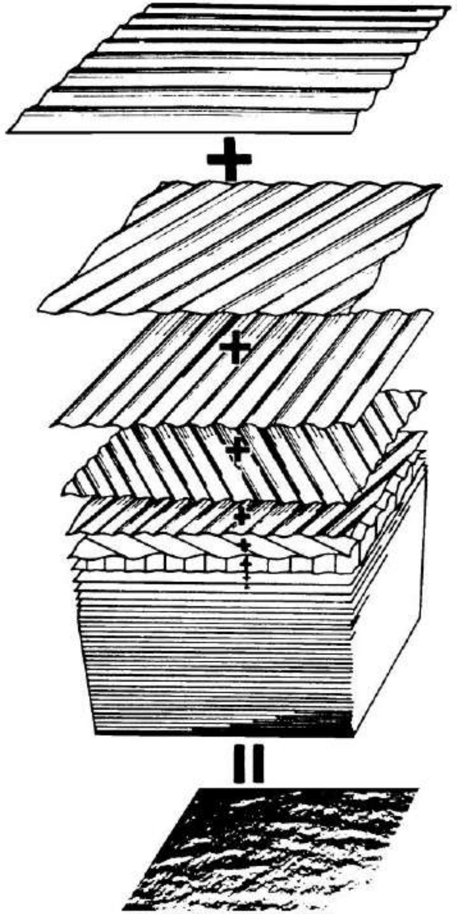
- Floating bodies → inertia of surrounding water to be included → added mass (and added moments of inertia) $m \rightarrow m_{dry} + a$
  calculated by diffraction software, e.g. WAMIT, NEMOH, DIFFRAC, AQWA

- Added mass depends on frequency and motion direction!

- $\omega_{heave} = \sqrt{\frac{c_{33}}{m+a_{33}}} = \sqrt{\frac{\rho g A_{wl}}{m+a_{33}}}$ ← Waterplane area
- $\omega_{pitch} = \sqrt{\frac{c_{55}}{J_{yy}+a_{33}}} = \sqrt{\frac{\rho g \nabla \overline{GM}}{J_{yy}+a_{55}}}$ ← Function of waterplane area, KG, KB, and ∇

Irregular Wind Waves

- apparently irregular
- but can be considered as a superposition of a finite number of regular waves
- each regular having own frequency, amplitude and propagation direction



Wave Excitation Forces

- Calculated by diffraction software and/or Morison equation

  Large-volume structure — Hydrodynamically transparent

- Depending on wave frequency and direction

- Per frequency expressed by force RAO (regular, monochromatic waves)

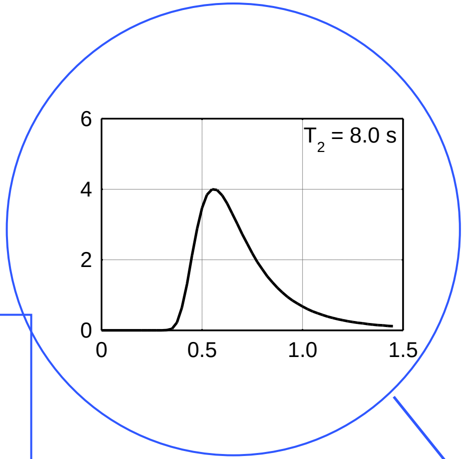
- Irregular waves → interaction between wave components of different frequency

→ (Sum and) <u>difference</u> frequency terms → low-frequency excitation (→ Quadratic Transfer Functions (QTF))

→ Mooring

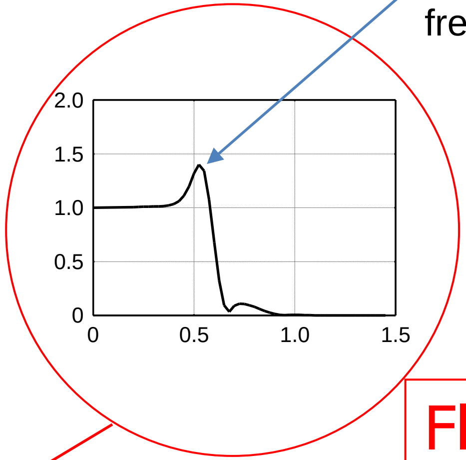
Motion Response in Irregular Waves

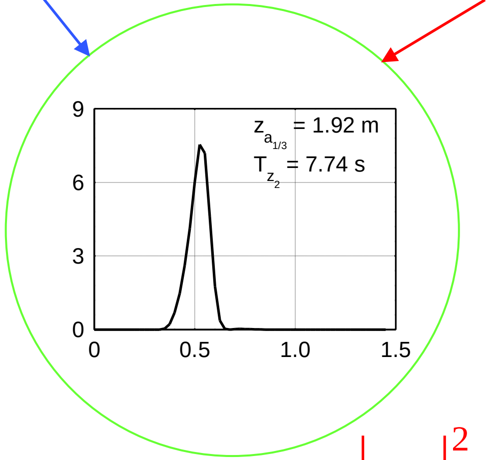
Waves: spectrum



Floater: RAO

Heave natural frequency





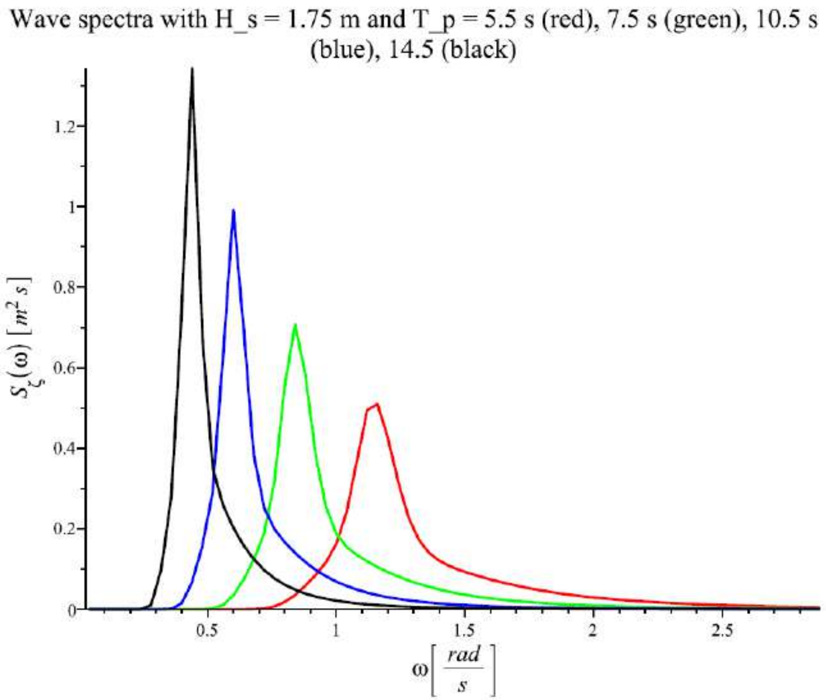
Floater response

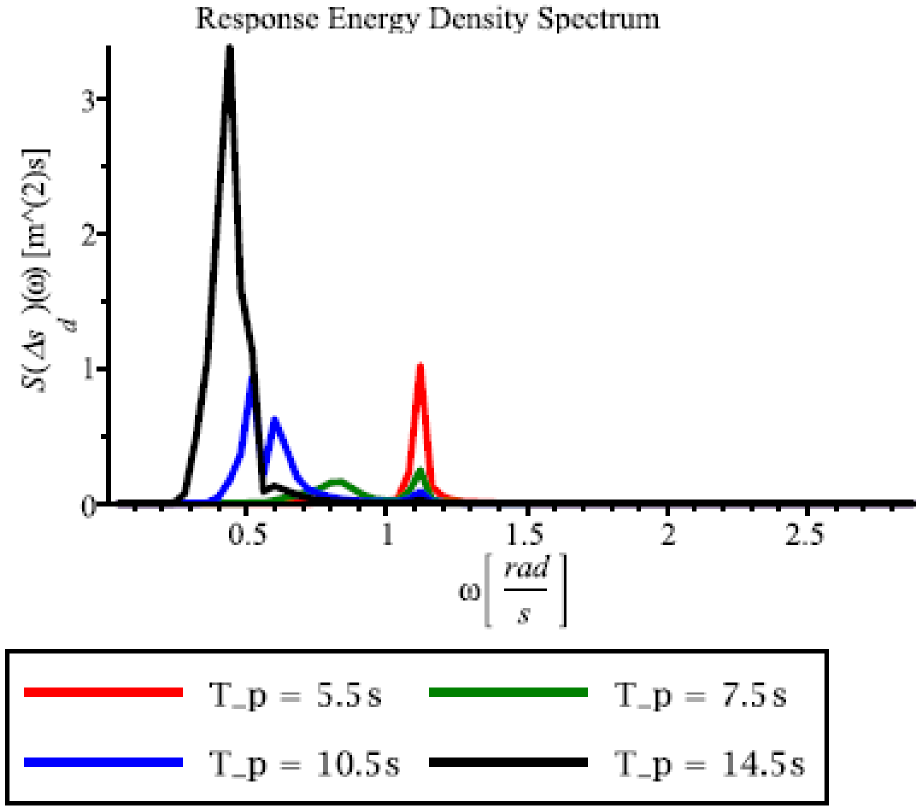
Floater design
→ Avoid wave frequencies
with Floater natural frequencies!

$$S_z(\omega) = S_\zeta(\omega)\left|\frac{z_a}{\zeta_a}\right|^2(\omega)$$

Response Depends on Input Sea State

- Different response spectra for sea state with different peak period
- Remember, the RAOs are only dependent on the system itself and the wave direction.





➔ Per wave spectrum peak period different limiting significant wave height!

Wave Scatter Table

Joint probability of Hs and Tp

Marginal probability of Tp

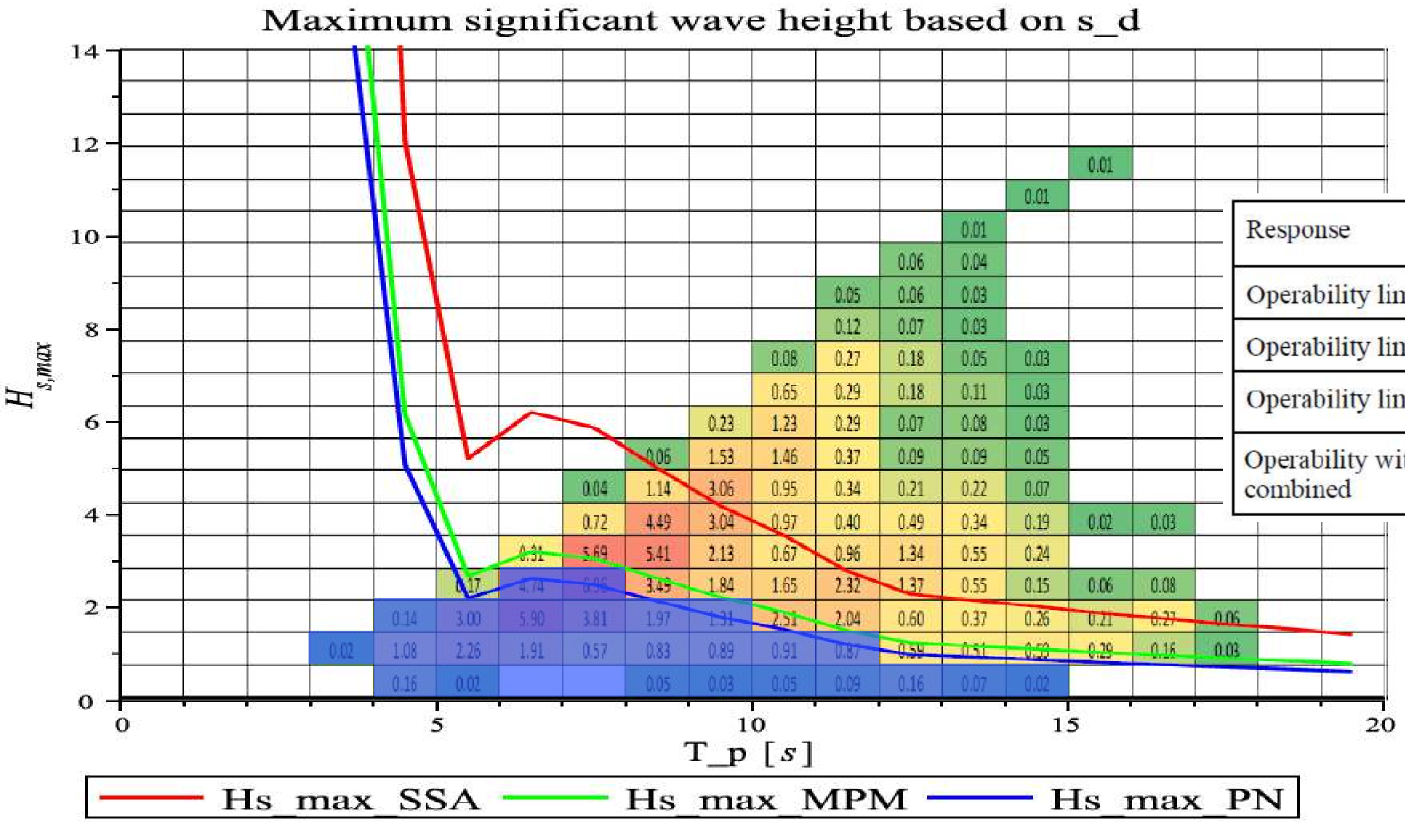
Marginal probability of Hs

Example Wave scatter table North Sea
Source: https://www.imarest.org/reports/650-metocean-procedures-guide/file
IMarEST, 2018. Metocean Procedure Guide for Offshore Renewables

Hs min/m	Hs max/m	Hs mid/m	0	0	0	0.02	1.38	5.45	12.86	17.79	17.44	14.06	11.13	8.41	5.47	3.05	1.67	0.59	0.54	0.09	0	0	99.95
13.3	14	13.65																					0
12.6	13.3	12.95																					0
11.9	12.6	12.25																					0
11.2	11.9	11.55														0.01					0.01
10.5	11.2	10.85													0.01						0.01
9.8	10.5	10.15												0.01							0.01
9.1	9.8	9.45											0.06	0.04							0.10
8.4	9.1	8.75										0.05	0.06	0.03							0.14
7.7	8.4	8.05										0.12	0.07	0.03							0.22
7	7.7	7.35									0.08	0.27	0.18	0.05	0.03						0.61
6.3	7	6.65									0.65	0.29	0.18	0.11	0.03						1.26
5.6	6.3	5.95								0.23	1.23	0.29	0.07	0.08	0.03						1.93
4.9	5.6	5.25							0.06	1.53	1.46	0.37	0.09	0.09	0.05						3.65
4.2	4.9	4.55						0.04	1.14	3.06	0.95	0.34	0.21	0.22	0.07						6.03
3.5	4.2	3.85						0.72	4.49	3.04	0.97	0.40	0.49	0.34	0.19	0.02	0.03				10.69
2.8	3.5	3.15					0.31	5.69	5.41	2.13	0.67	0.96	1.34	0.55	0.24						17.30
2.1	2.8	2.45					0.17	4.74	6.96	3.49	1.84	1.65	2.32	1.37	0.55	0.15	0.06	0.08			23.38
1.4	2.1	1.75				0.14	3.00	5.90	3.81	1.97	1.31	2.51	2.04	0.60	0.37	0.26	0.21	0.27	0.06		22.45
0.7	1.4	1.05			0.02	1.08	2.26	1.91	0.57	0.83	0.89	0.91	0.87	0.59	0.51	0.59	0.29	0.16	0.03		11.51
0	0.7	0.35				0.16	0.02			0.05	0.03	0.05	0.09	0.16	0.07	0.02					0.65
Tp mid/s			0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	
Tp min/s			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Total
Tp max/s			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	

Operability

On basis of limiting wave heights, assess in which percentage of time the operation is possible. → Sum of wave occurrence below the limit curves.



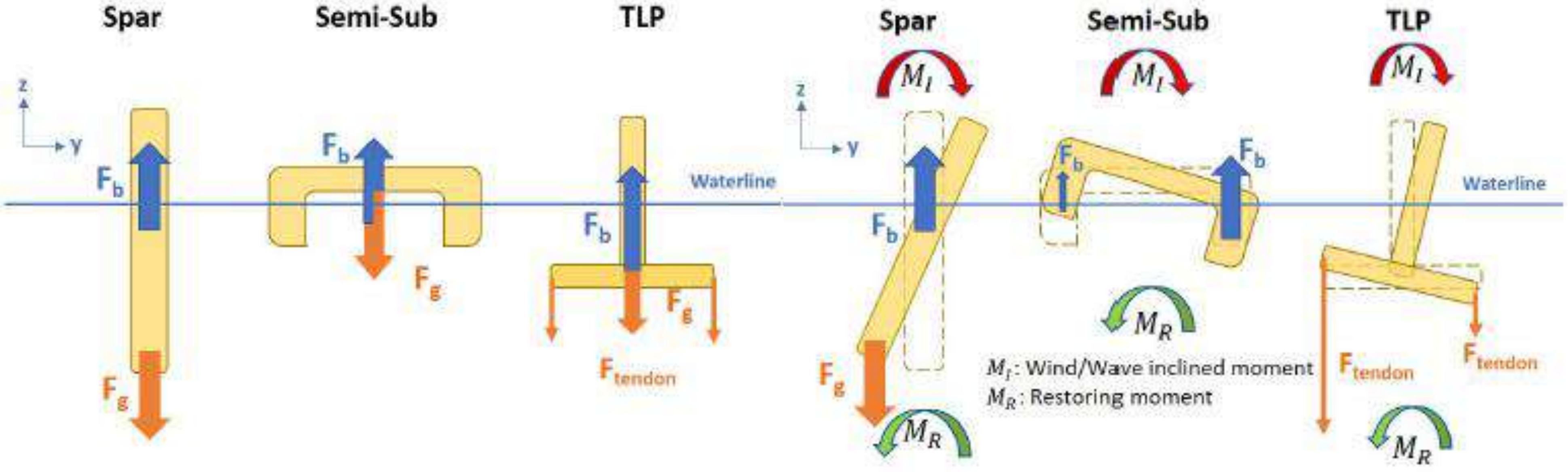
Response	monopile-hull clearance s_d
Operability limited by *SSA*	*OP_ind*[*iSD*, *iSSA*] = 79.4
Operability limited by *MPM*	*OP_ind*[*iSD*, *iMPM*] = 46.0
Operability limited by P_N	*OP_ind*[*iSD*, *iPN*] = 37.8
Operability with all limits combined	

Different Floater Concepts

Figure 2.5: The three floater foundation concepts. Spar-buoy (Spar), Semi-submersible (Semi-Sub) and Tension Leg Platform (TLP) [22]

[22] B. Speer, D. Keyser, and S. Tegen. *Floating Offshore Wind in California: Gross Potential for Jobs and Economic Impacts from Two Future Scenarios Strategic Partnership Project Report*. 2015. URL: http://www.boem.gov/Pacific-Completed-Studies/..

Floater Stability



Offshore Installation of Wind Turbines on Floating Foundations

Literature Review

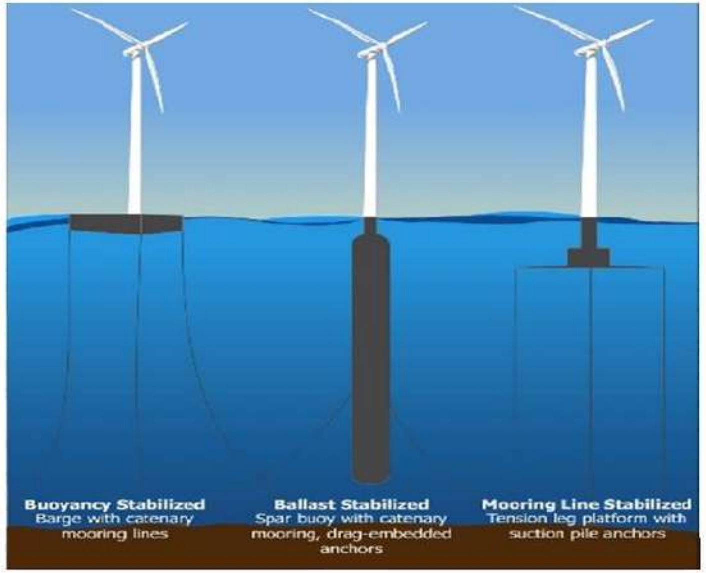
by

Q. van Suijlen

ODE Literature Research OE54010-20

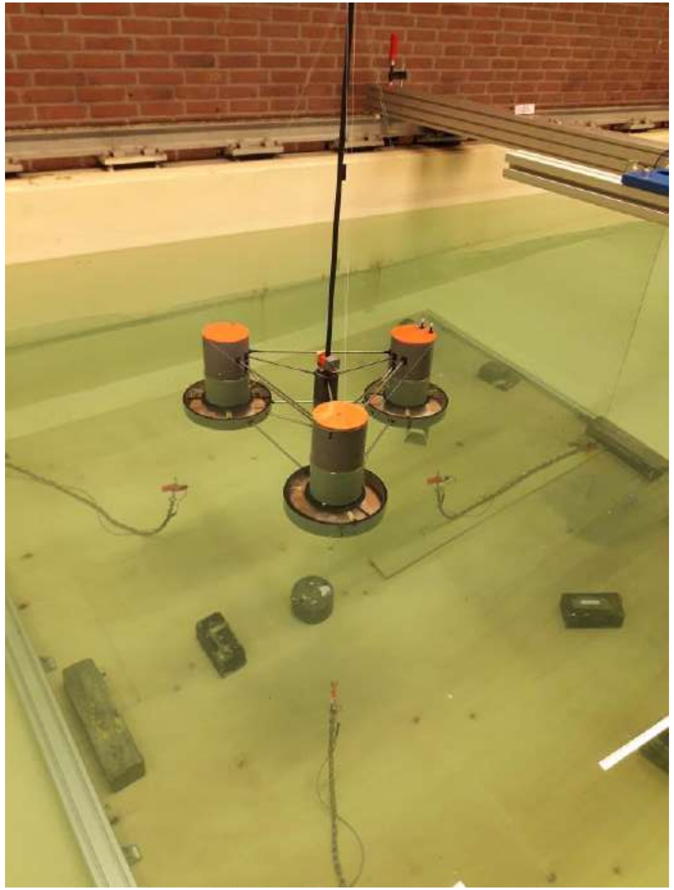
Mooring Systems

Floating Offshore Wind Turbines



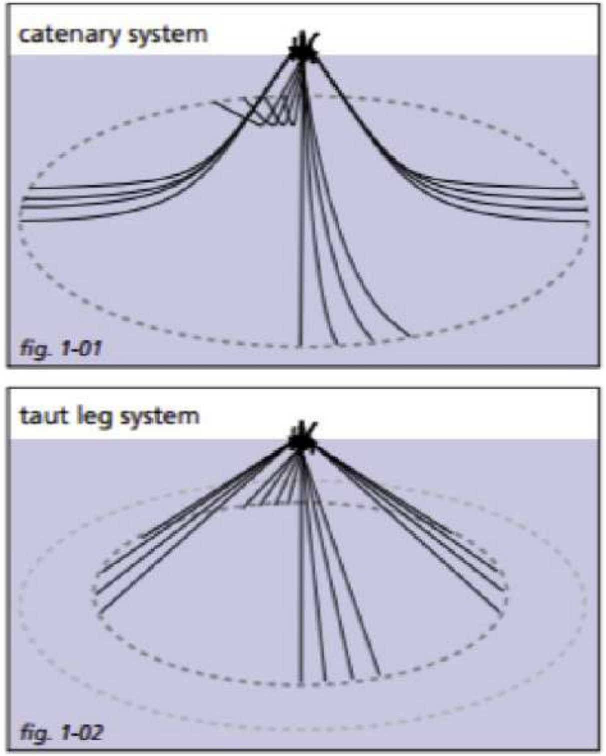
Floating Wind Turbine

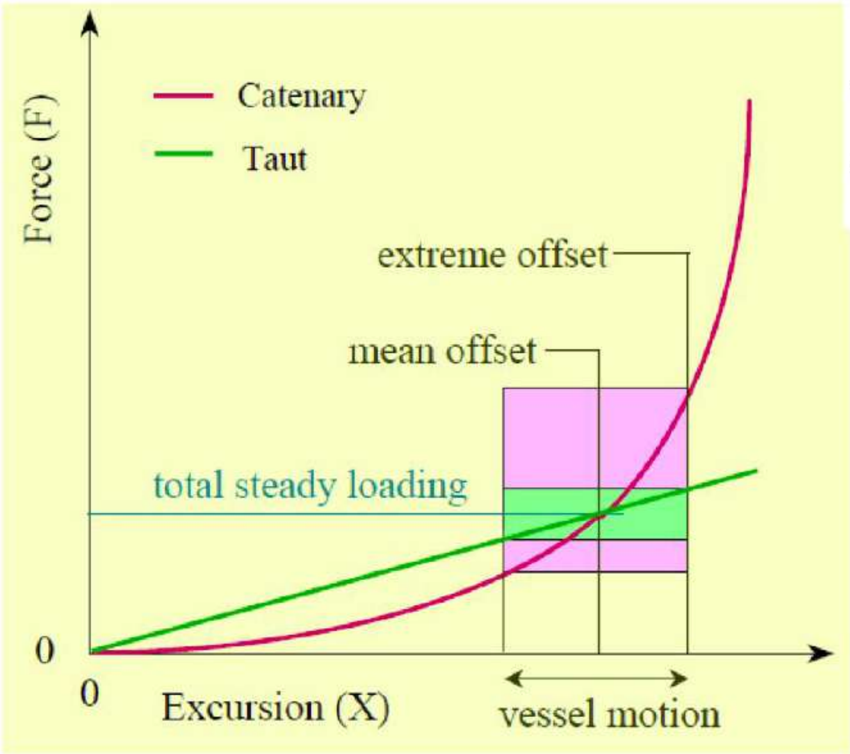
Master thesis Youri Metsch

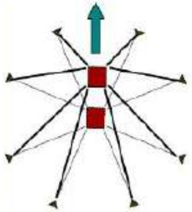


Mooring System – Load-Excursion Curve

- The static load-excursion curve defines the basic mooring characteristics
- Typically a non-linear curve for catenary moorings and a more linear curve for taut-mooring polyester systems

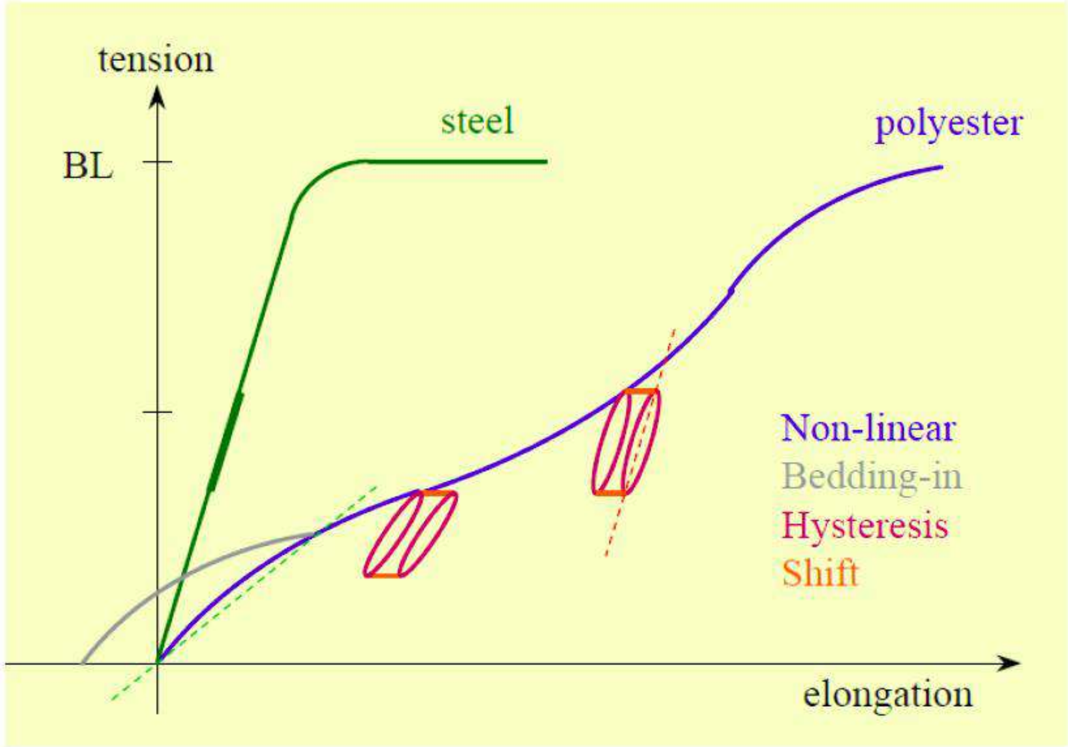






Mooring Line – Tension-Elongation Curve

- Material properties of steel (chain and wire) is (more) linear, but the resultant catenary shape of the mooring line results in the non-linear load-excursion curve → Bottom chain lift
- Versus, the non-linear line stiffness of polyester, which can results in a linear load-excursion curve



Catenary system

- stiffness from weight and lift of bottom chain

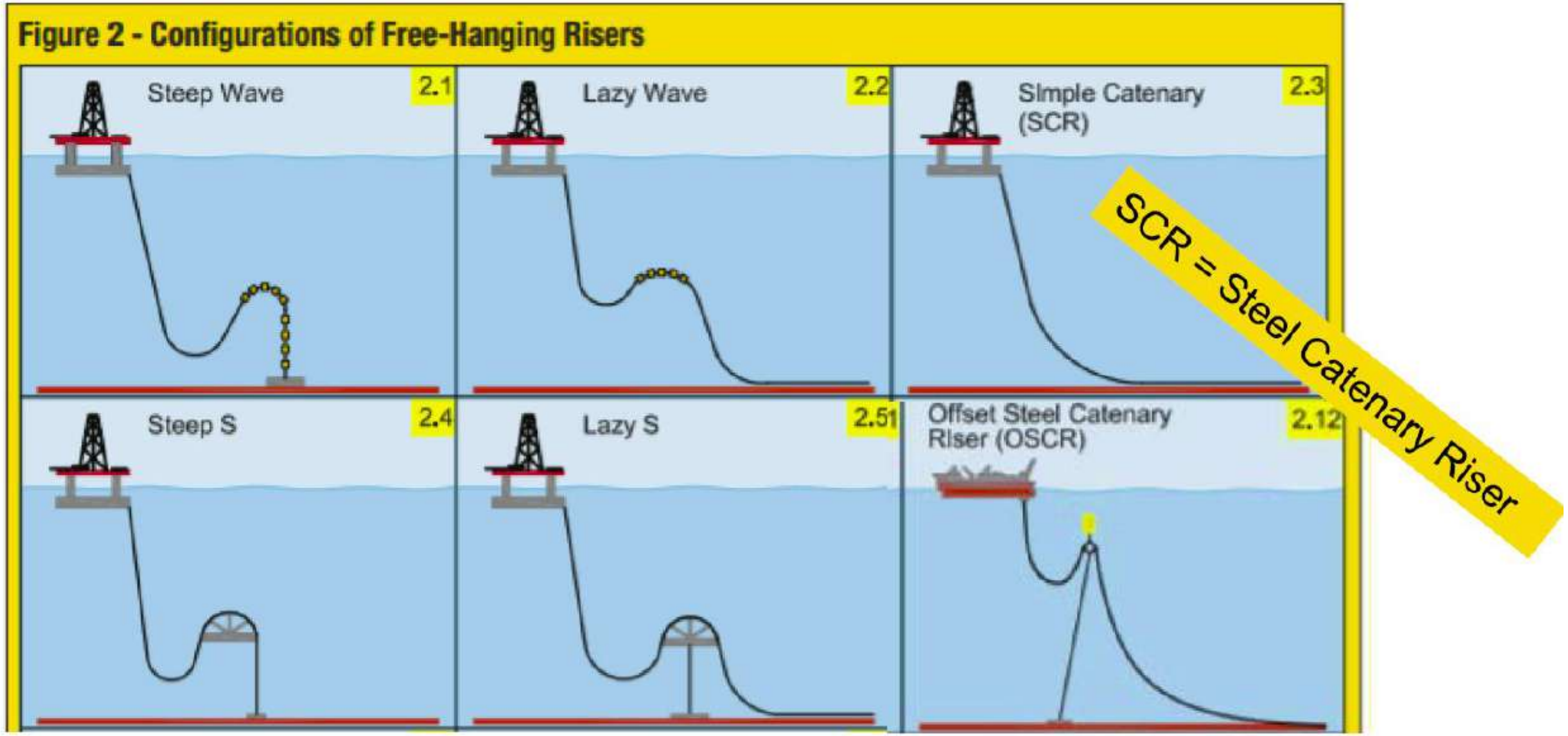
Taut-mooring system

- stiffness from elasticity of the mooring line

BL – breaking load

Load-Excursion Curve – Risers (Power Cables)

- To include the effect of cables without any computational effort, the calculated static load-excursion curve from the cable system alone can be used as external-force input to the mooring system.
- Many different cable configurations: Coupled and Decoupled. Inspired by Offshore O&G
- Note: Cables are not designed to withstand mooring loads
  → much smaller horizontal forces than mooring lines



Moored Floater Response - Dynamics

- Mass-spring system for dynamic motions

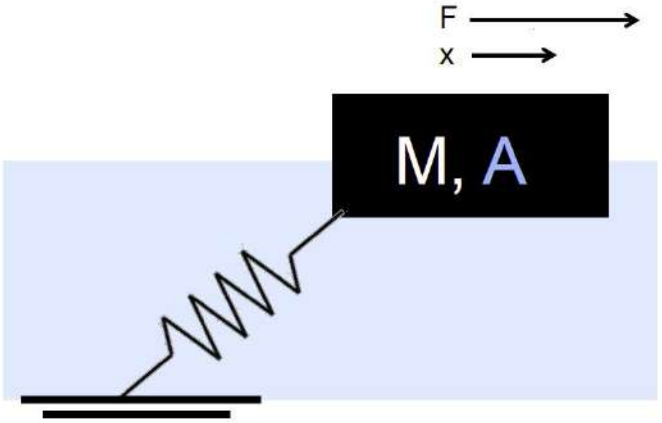
$$\vec{F}_{ext} = \mathbf{M}_{floater}\ddot{\vec{x}} + \mathbf{C}_{mooring}\vec{x}$$

- Consider 1-DOF surge motion equation, uncoupled

$$F_1 = (M + A_{11})_{floater}\ddot{x}_1 + C_{11,mooring}x_1$$

- Natural period of the mooring system

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{(M + A_{11})_{floater}}{C_{11,mooring}}}$$



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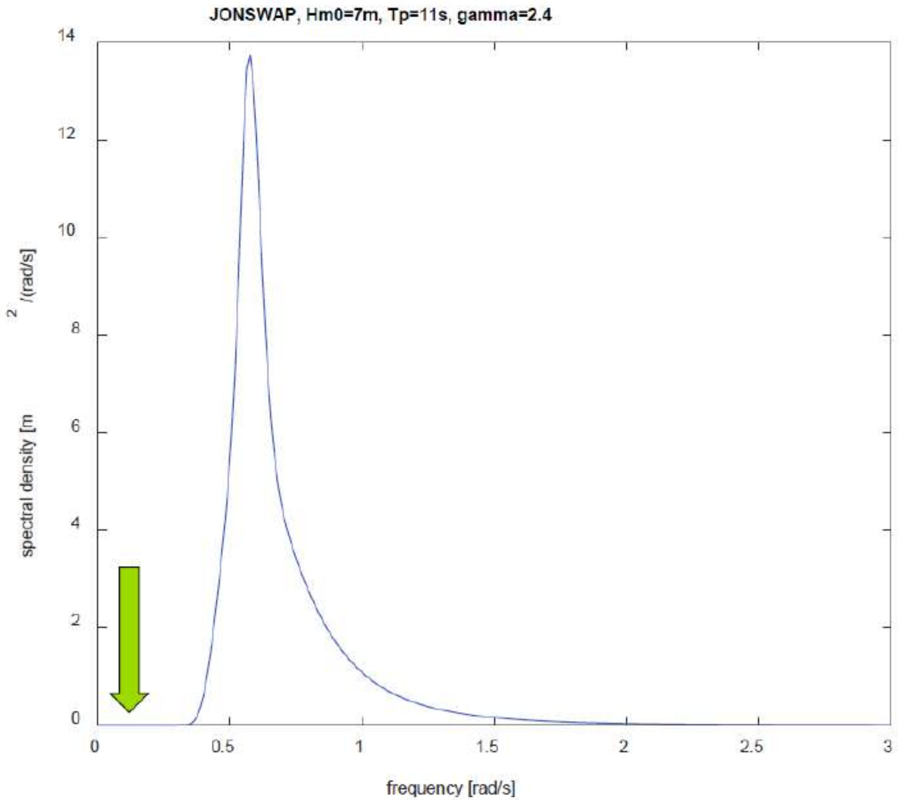
Moored Floater Response

- First order wave loads (Froude-Krylov & diffraction) are large!
- Target for the mooring design: avoid these forces

→ Create a mooring system such that the natural period is outside the wave excitation by at least a factor 4 to 5, to avoid direct wave excitation.



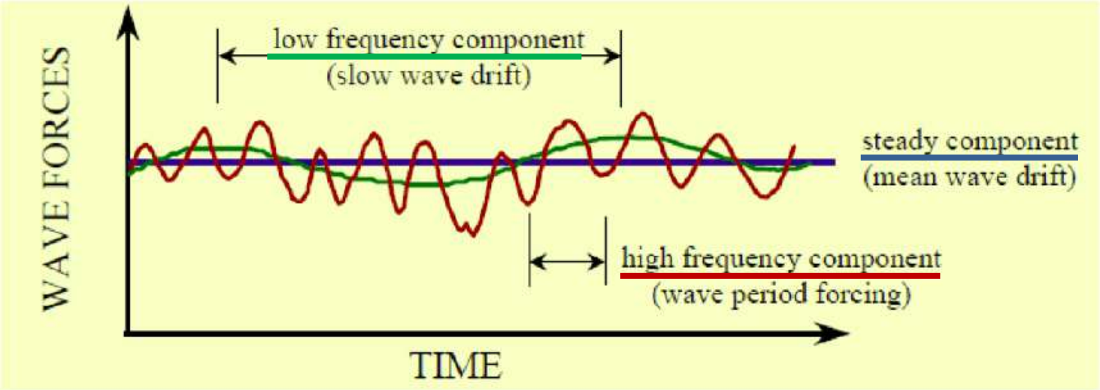
Typical mooring natural period $T = 100\text{ s}$

$$\omega = \frac{2\pi}{T} = 0.0628\text{ rad/s}$$

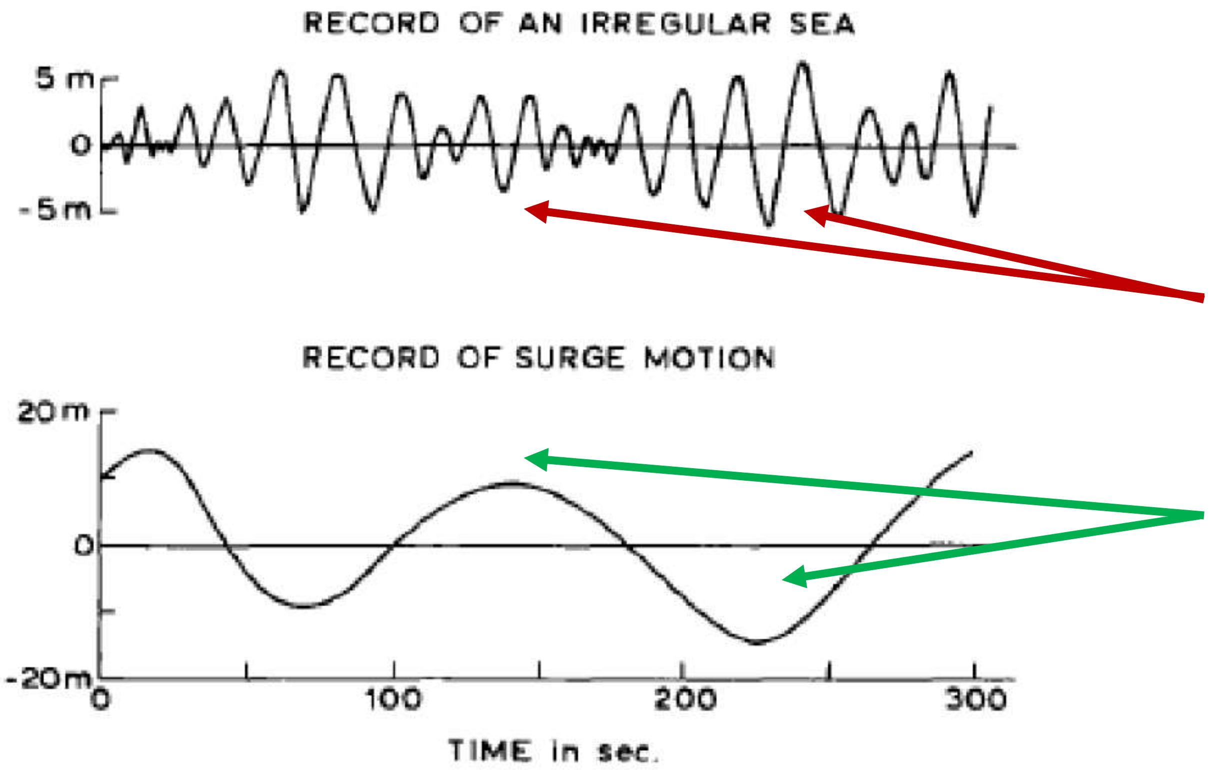
But: Irregular waves also have low-frequency excitation!

Low-Frequency Wave Excitation

- Discussed in Motions and Loading MT44020 – Part 2
- Wave drift = Second order force
  - Result of pressure integration on the mean wetted hull, accounting for perturbation of pressure, motions, wet/dry in splash zone
  - First order pressures in regular waves
    → resultant force over one oscillation ≠ 0
    → mean second order wave drift force → Quadratic Transfer Function (QTF)
    This will only lead to a mean offset of the floater in the mooring system
- Irregular wave concept
  - Summation of two waves with nearly the same frequency will give a signal beat with a low frequent component (and a high frequent component)
  - Low wave frequency leads to low-frequency wave load → mooring excitation



Low-Frequency Response

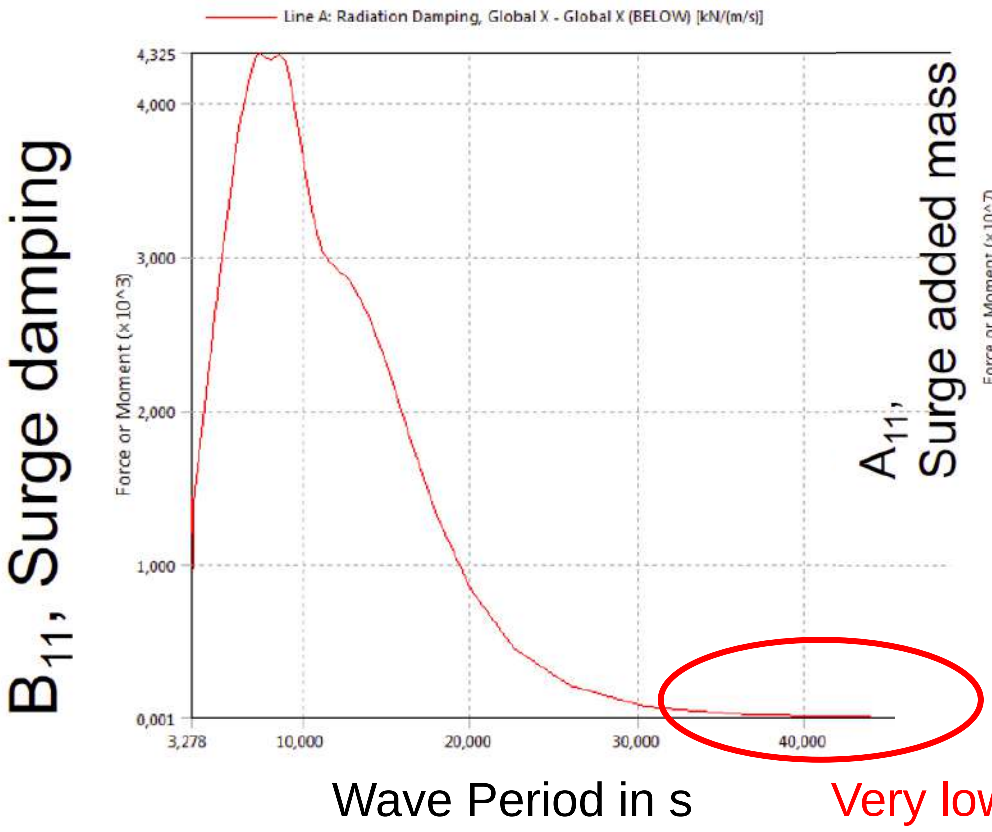


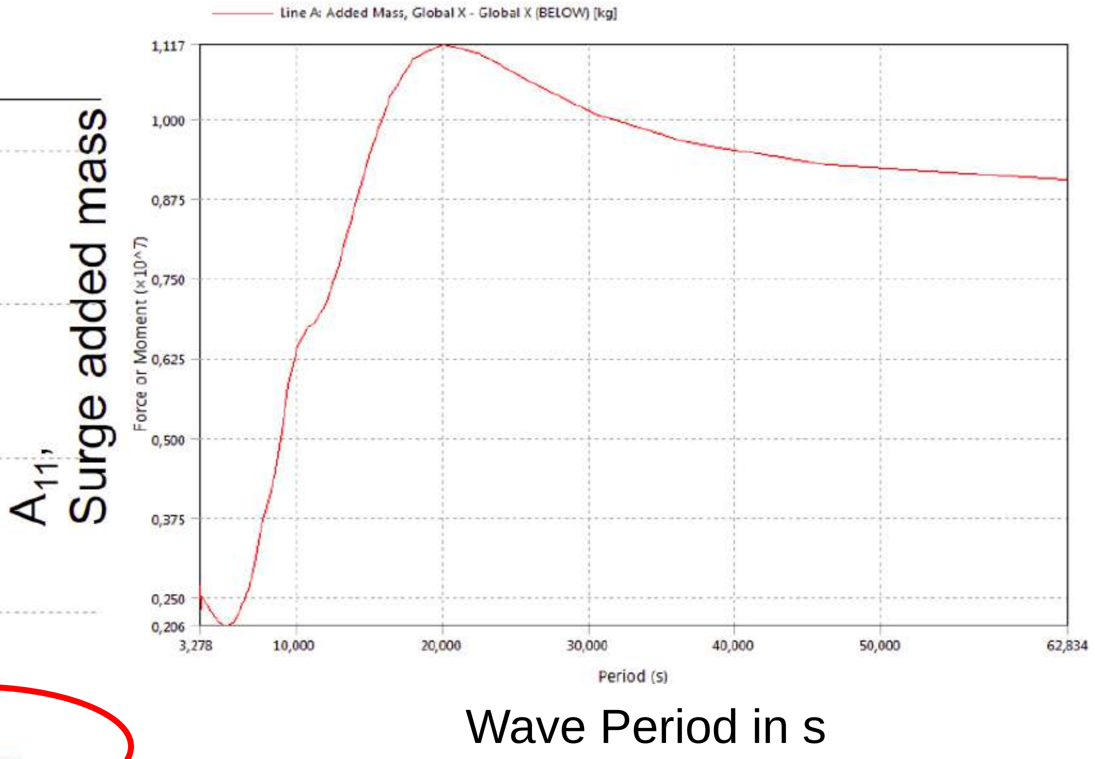
- Beating pattern in wave elevation
- Variation in wave loads and response

PhD thesis Pinkster: Low frequency surge motion of moored LNG carrier in irregular head seas, http://resolver.tudelft.nl/uuid:d6d42e9c-c349-47e5-8d63-5c6454196b04

Moored Floater Response – Damping

- Problem: at very long oscillation periods (in this example above 40 sec) there is hardly any wave radiation damping





Damping Sources for Low-Frequency Motions

Main sources for low-frequency damping

- Viscous damping on the hull (friction)
- Wave drift damping
- Mooring line damping, including bottom friction

- Only fully empirical or semi-analytical formulations; application is limited and needs validation

- Viscous damping
    - Modelled together with current loads. Based on relative fluid velocity

- Wave drift damping (relating wave drift force to slow floater motion)
    - Obtained from drift forces and their derivatives

- Mooring line damping
    - Can be estimated based on line dynamics and drag formulations
- Damping included in dynamic mooring analysis (time domain)

Environmental Load Components

Com-ponent	Loading Description	Fluctuations in 3hour sea state	Response
Wind	10-min mean wind velocity (m/s)	Prescribed wind spectrum	Mean offset + low frequent oscillations
Current	Mean current velocity (m/s)	Often assumed zero	Mean offset
Waves	1st order wave load	Irregular 1st order load; wave spectrum	Zero mean + wave frequent oscillations
	2nd order wave load = drift load	Low frequent 2nd order load variations; wave grouping	Mean offset + low frequent oscillations

Installation

Port Assembly and Tow-out

- Floater and turbine assembled at quay-side
- Towed to location
- Moored in place

Requires

→ (very) deep-water port

→ Floater stability in towed condition

On-site Assembly

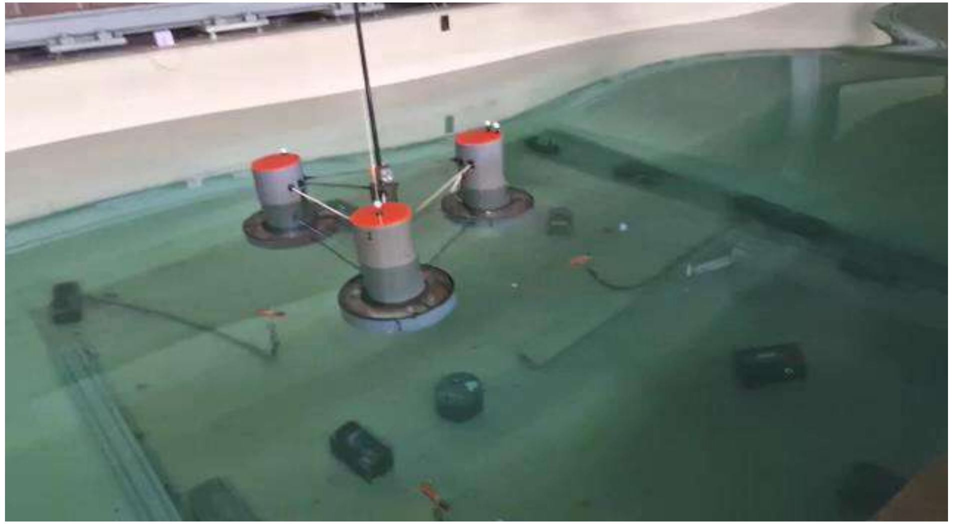
- Floater and turbine assembled at offshore location
- Floater towed to location and moored
- Tower and RNA installed later

Requires

→ High lifting capacity crane vessel

→ Floating to floating installation

Model Testing – Ongoing MSc thesis



Experimental Motion Analysis of a Floating Offshore Wind Turbine

under the Influence of Waves, (simulated) Wind Loads, and its Mooring System

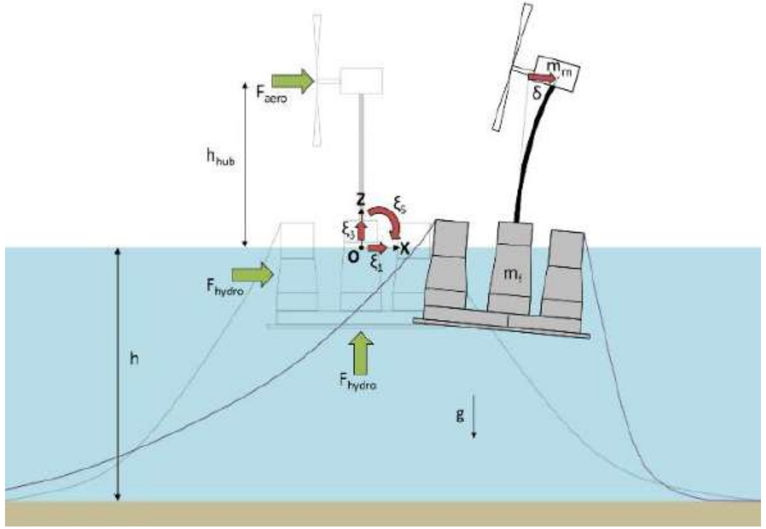


Figure 1: Impression of forces and response on a FOWT.
From: Pegalajar-Jurado, A., Borg, M., and Bredmose, H.: An efficient frequency-domain model for quick load analysis of floating offshore wind turbines, Wind Energ. Sci., 3, 693–712, https://doi.org/10.5194/wes-3-693-2018, 2018, licensed under CC. BY.

Reading Material

- Journée, JMJ, Massie, WW, Huijsmans, RHM (2015). Offshore Hydromechanics, 3rd edition.
- Holthuijsen, LH (2007). Waves in Oceanic and Coastal Waters. → e-book available via TU Delft Library: https://tudelft.on.worldcat.org/search?queryString=%22Waves+in+Oceanic+and+Coastal+Waters%22#/oclc/663973262 or
- https://app-knovel-com.tudelft.idm.oclc.org/web/toc.v/cid:kpWOCW0002/viewerType:toc//root_slug:waves-in-oceanic?kpromoter=marc
- Ma, K-T, Luo, Y, Kwan, T, Wu, Y (2019). Mooring System Engineering for Offshore Structures. → available via Science Direct: https://www.sciencedirect.com/book/9780128185513/mooring-system-engineering-for-offshore-structures