TWIND Summer School

Floating Offshore Wind
Design solutions and Higher-order hydrodynamics

6/07/2021 | Daniel Milano

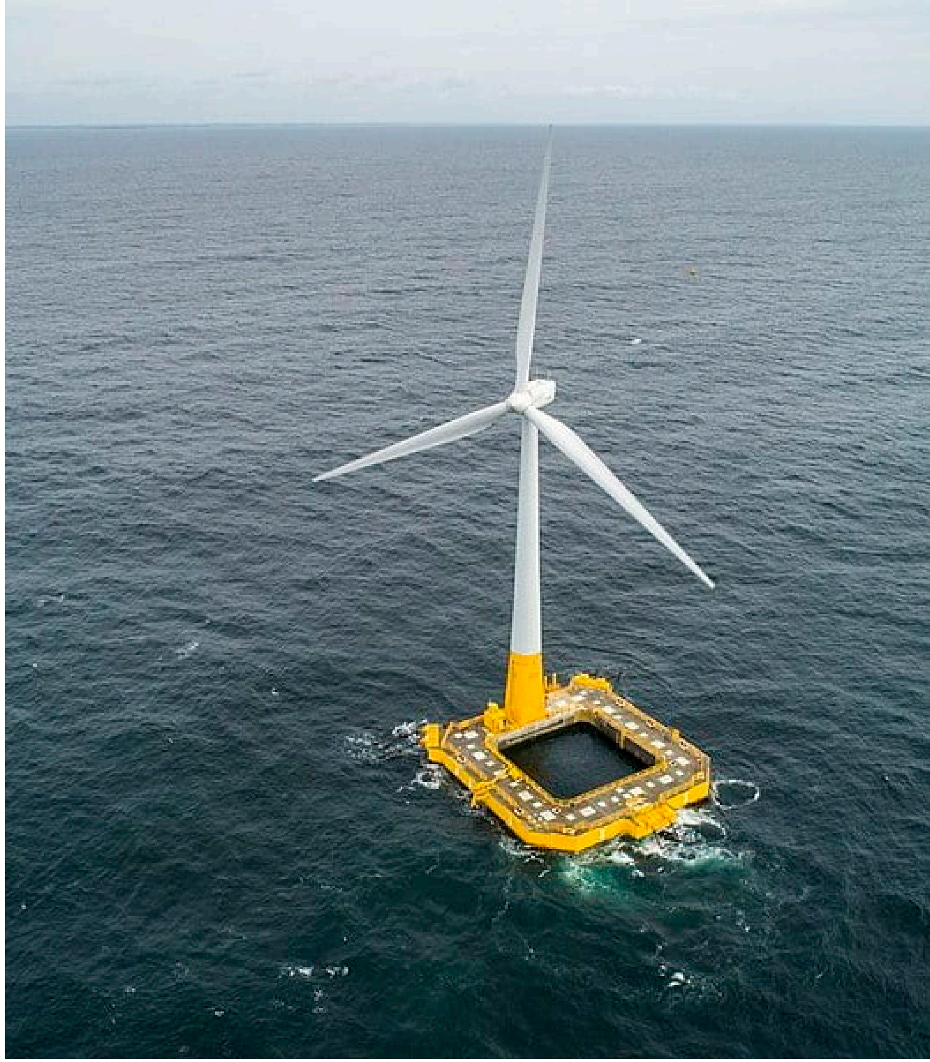
CATAPULT Offshore Renewable Energy

Floating wind power

The offshore wind industry transitioning from fixed to floating, following oil & gas footsteps

Why go floating?

- **Access to deep-water sites**: access to large areas with water depths of 60 m or more
    - Strong and steady winds
    - Proximity to densely populated coastal areas
- **Design**: alternative to bottom-fixed in mid-depth sites (30 - 60 m)
- **Construction and operation**: possibility of assembly on-quay and easy transport using towing vessels
- **Bathymetry sensitivity**: less sensitive to local constraints, mooring system is the only element in direct contact with seabed
- **Social and visual impact**



Ideol Floatgen Floating Wind Turbine

Agenda

- **Design**
- Challenges

Fukushima FORWARD | 5MW, Osaka 2016
Photo: Yumiuri Shimbun

Design

- Floater and transition piece: buoyancy and structural support
- Mooring and anchoring system: station keeping
- Dynamic power cable:

  grid connection

Trade-off between stability and costs depending on floater's size

- Small draft and small diameter: lower hydrostatic stability
- Large draft and diameter: higher manufacturing costs

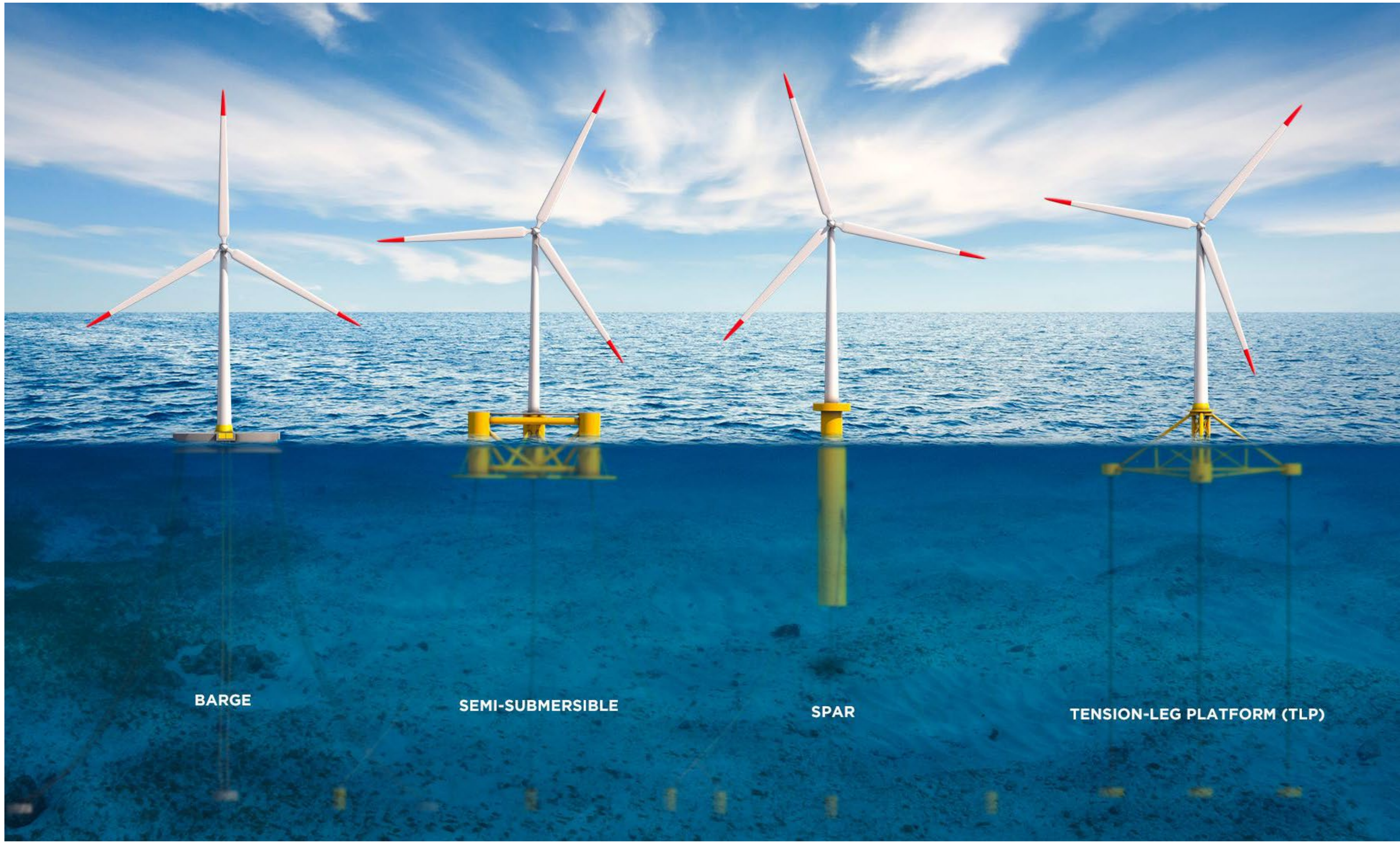


Photo: Green Giraffe

A. R. Henderson, D. Witcher, and C. A. Morgan. Floating support structures enabling new markets for offshore wind energy. In European Wind Energy Conference, Marseille, France, 2009

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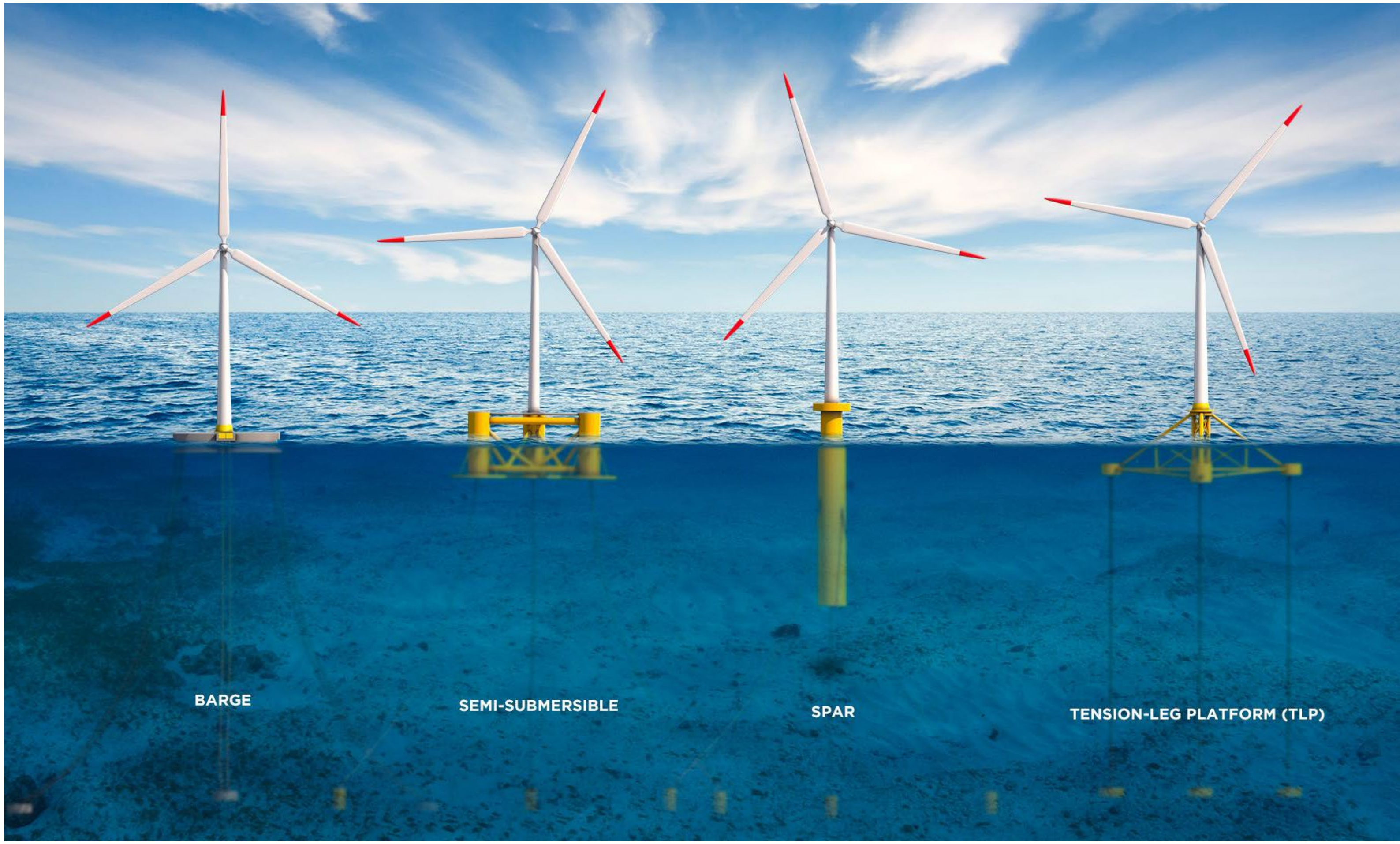
Geometry of the floating platform impacts motion response and structural behaviour of FOWTs

- **Slender spar buoys**
  (large draft, small diameter)
  - Prone to fatigue
- **Barge structures**
  (small draft, large diameter)
  - Large heave and pitch motion responses
- **Tension-leg platform**
  (small draft, small diameter)
  - Reduced motion responses due to stiff, pre-tensioned mooring system



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Multidisciplinary system

- Servo – aerodynamics (Blade element - momentum theory)
  - Blade loading
  - Control system (blade pitch, yaw, torque)
  - Drivetrain & Power generation
- Hydrodynamics (Potential flow theory + Morison quadratic drag)
  - Wave excitation: Froude-Krylov
  - Incident-wave scattering: diffraction
  - Wave acceleration forces: added mass
  - Radiation damping
  - Wave velocity forces: drag
  - Hydrostatic restoring forces
- Mooring system (quasi-static or dynamic)
  - Station keeping forces

Umaine 15 MW VolturnUS Semi-sub

Example: pitching & counter-pitching FOWTs

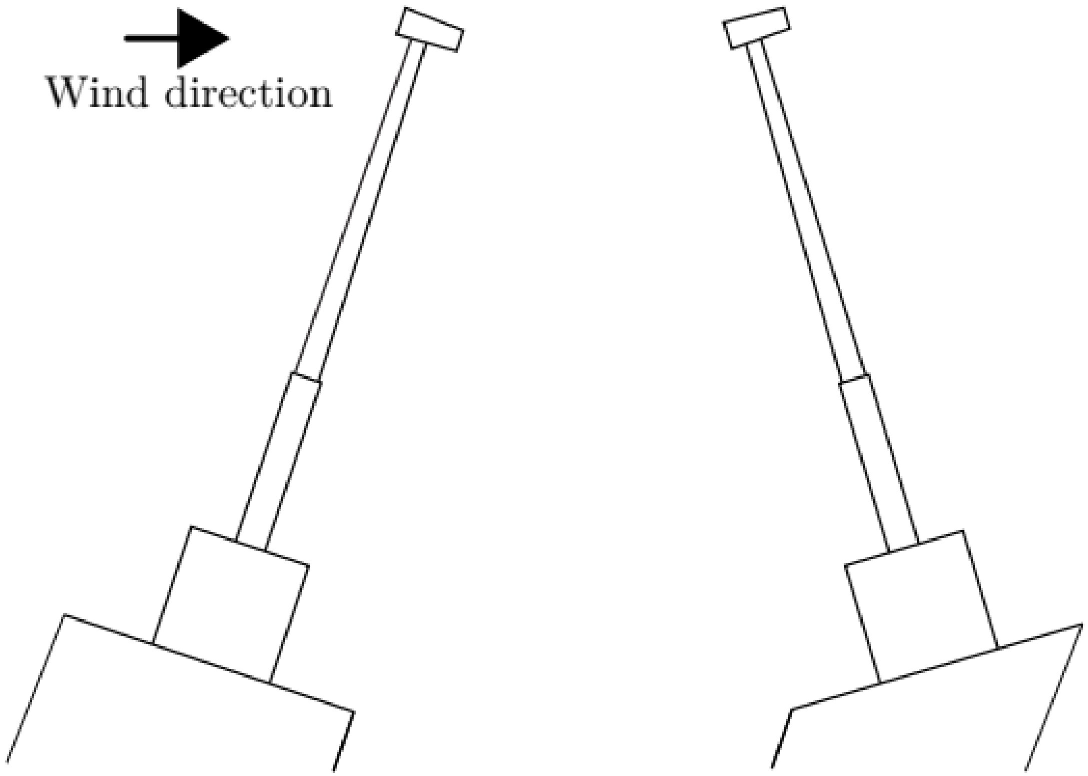
Wind-induced motion response for TLP wind turbine designs

Pitching

- Positive keel-to-nacelle vector component following wind
- Rotor leans away from the wind

Counter-pitching:

- Negative keel-to-nacelle vector component following wind
- Rotor leans towards the wind

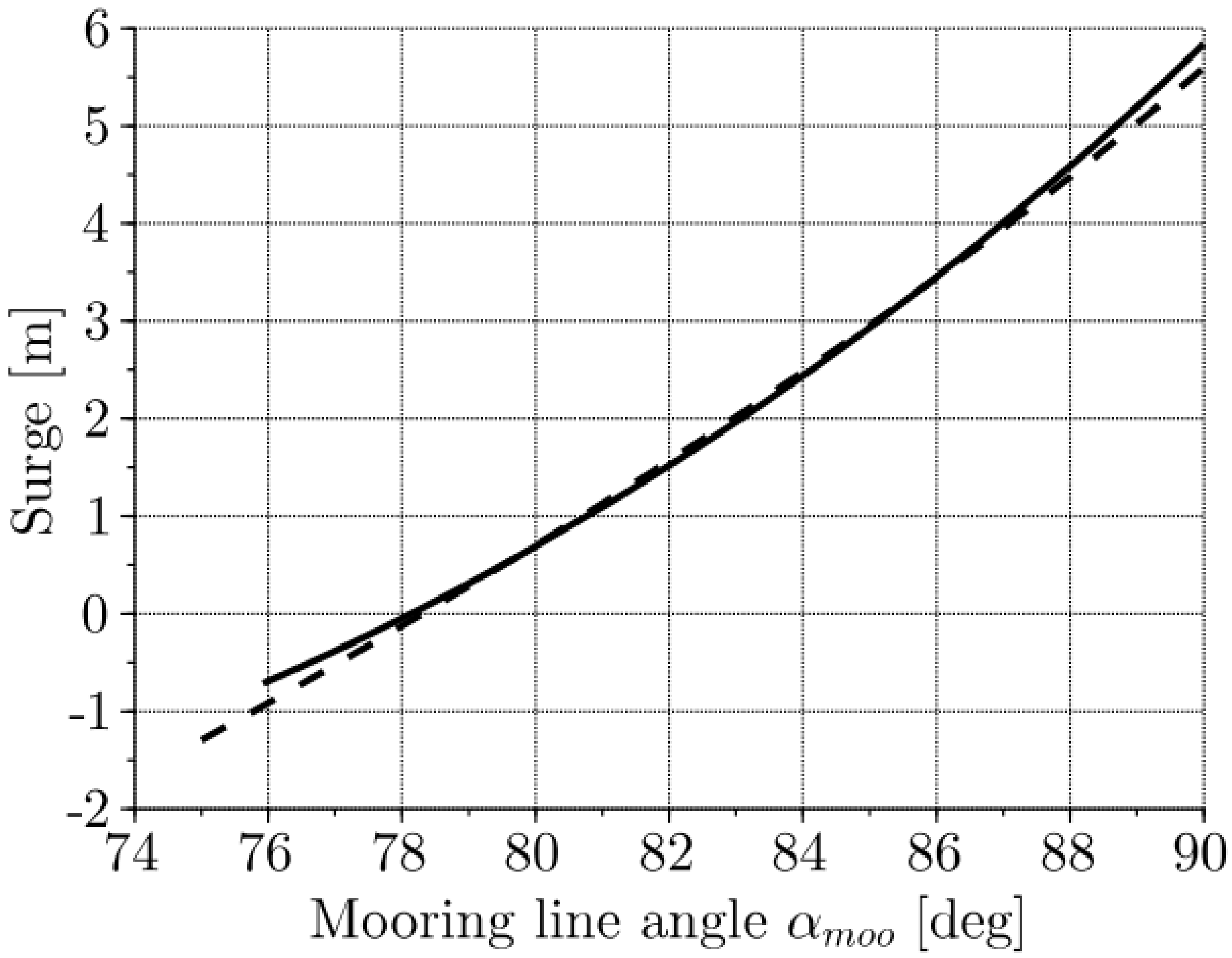


(a) Pitching (b) Counter-pitching

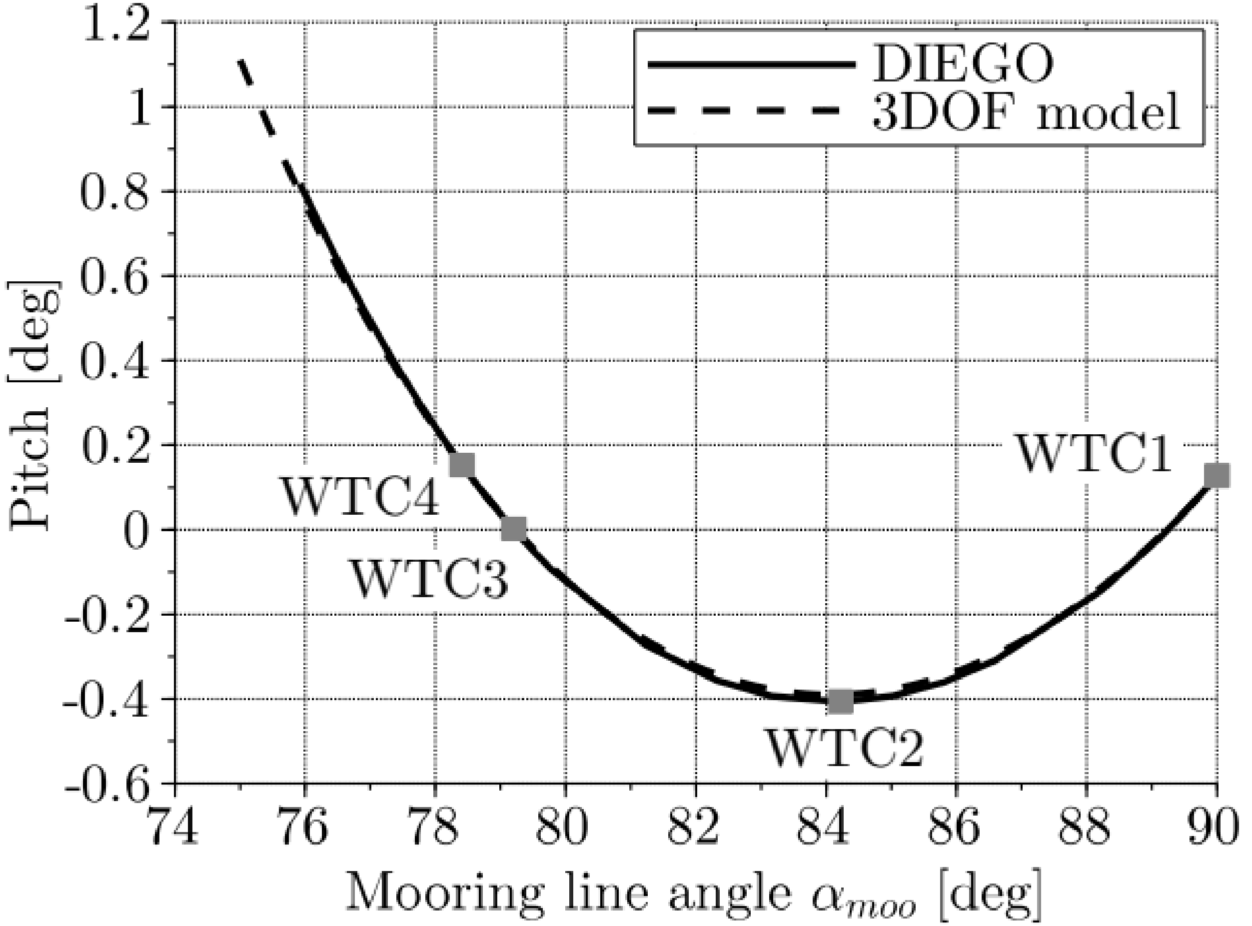
Pitching and counter-pitching wind response

D. Milano. A Numerical Prototype for Floating Offshore Wind Turbines, Industrial Doctoral Centre for Offshore Renewable Energy, 2021

Example: pitching & counter-pitching FOWTs



(a) Surge displacement



(b) Pitch displacement

Pitching response at varying tendon inclination

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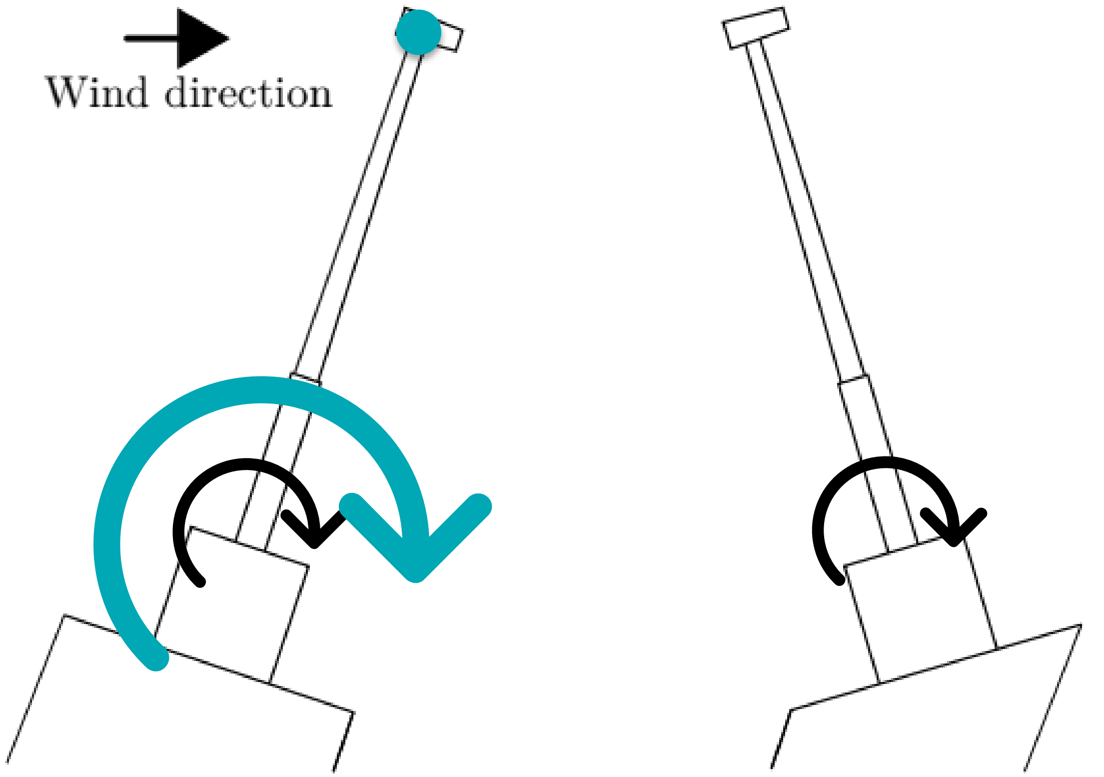
Gravity

- A keeling wind turbine is subject to gravity forces
- Bending moments at tower bottom



(a) Pitching (b) Counter-pitching

Pitching and counter-pitching wind response

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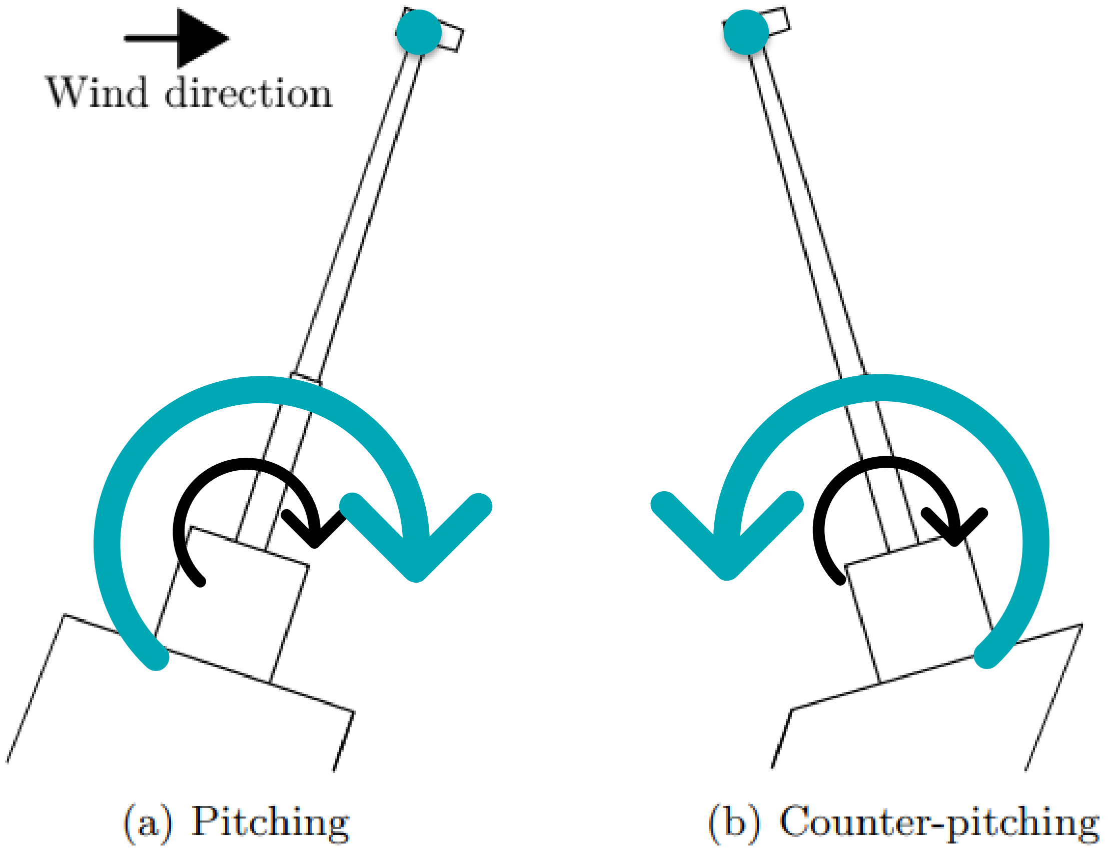
Gravity

- A keeling wind turbine is subject to gravity forces
- Bending moments at tower bottom
- In counter-pitching configuration, wind heeling moment can help offset gravity-based tilting moment

TLPs are better, right?



Pitching and counter-pitching wind response

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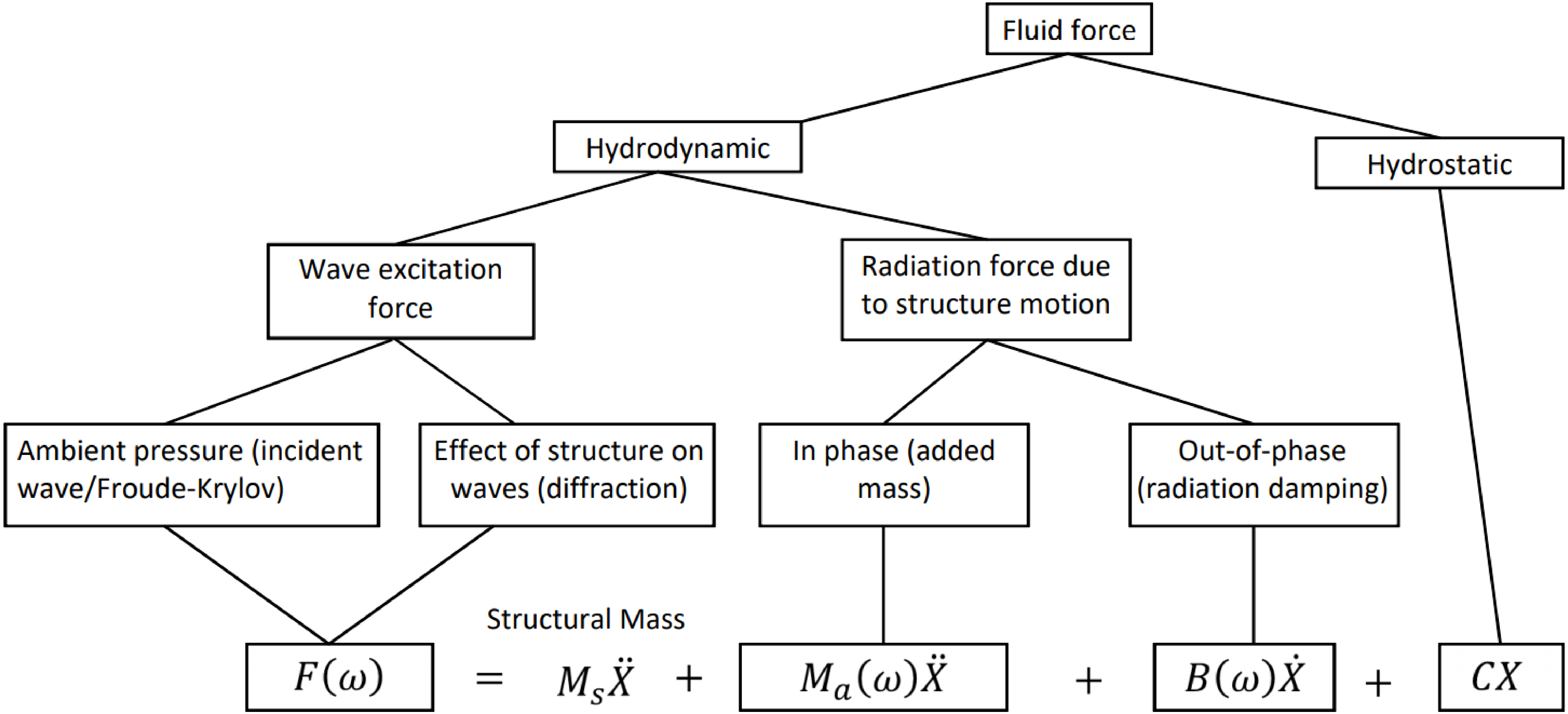
Agenda

- Design
- Challenges

Ocean Valiant drilling platform | Shetland, 2016
Photo: gCaptain

Enhanced hydrodynamics



Equation of motion

Enhanced hydrodynamics

Wave elevation

$$\eta^{(1)}(t) = \sum_i A_i \, \cos(k_{x,i}\, x + k_{y,i}\, y - \omega_i\, t + \varphi_i)$$

Linear wave load

- Motion-agnostic

$$F_{ID}^{(1)}\,(t) = \sum_i A_i\, Fe_i\, \cos(k_{x,i}\, x + k_{y,i}\, y - \omega_i\, t - \theta_i\, + \varphi_i)$$

- TLPs plane motions (heave, roll and pitch) in the order of 2 - 5 sec
- Low amount of wave energy carried in this frequency interval
- Limited exciting forces obtained from linear diffraction-radiation models

- **However**, experimental studies have shown:
    - High-frequency resonant responses at double the wave periods, in the 4 - 10 sec interval
    - Slow drift forces, similar to an additional sea current

Froude-Krylov and Diffraction forces

1st order

Enhanced hydrodynamics

Wave elevation

$$\eta^{(1)}(t) = \sum_i A_i \cos(k_{x,i}\, x + k_{y,i}\, y - \omega_i\, t + \varphi_i)$$

Linear wave load

- Motion-agnostic

$$F_{ID}^{(1)}(t) = \sum_i A_i\, Fe_i \cos(k_{x,i}\, x + k_{y,i}\, y - \omega_i\, t - \theta_i + \varphi_i)$$

Quadratic wave load

- Motion-dependent
- Enhanced with FOWTs

$$F^{(2)}(t) = \sum_i \sum_j A_i\, A_j\, QTF^{+}(\omega_i;\omega_j) \cdot \cos[(k_i + k_j)\, x - (\omega_i + \omega_j)\, t + (\varphi_i + \varphi_j) + \varphi(\omega_i;\omega_j)_{QTF+}]$$
$$+ \sum_i \sum_j A_i\, A_j\, QTF^{-}(\omega_i;\omega_j) \cdot \cos[(k_i - k_j)\, x - (\omega_i - \omega_j)\, t + (\varphi_i - \varphi_j) + \varphi(\omega_i;\omega_j)_{QTF-}]$$

Froude-Krylov and Diffraction forces
1st and 2nd order

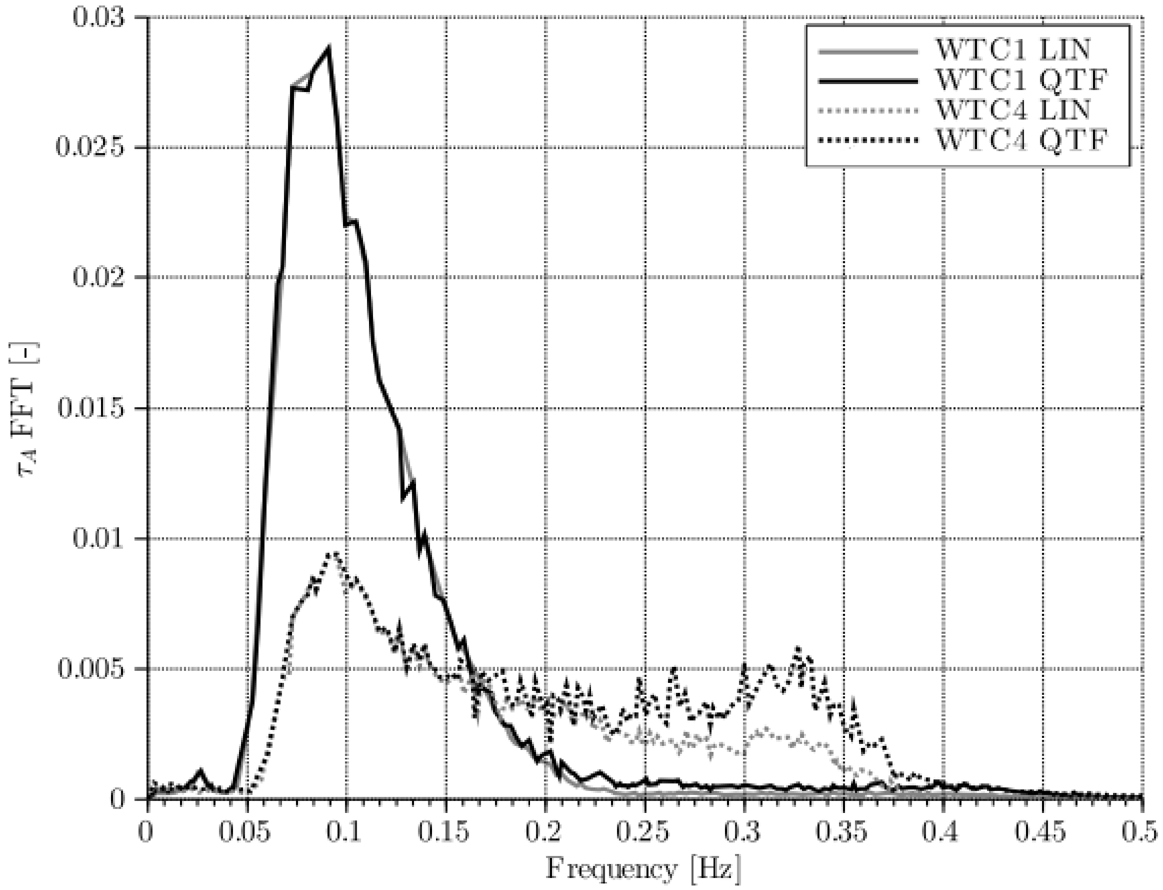
Enhanced hydrodynamics

Springing (TLP only)

- High-frequency resonant effect
- Observed when the peak period of the sea state is approximately twice the structure’s natural period in heave, pitch or roll
- Mainly impacts TLP structures on tendon fatigue consumption, a key design aspect

Slow-drift forces (all FOW designs)

- Low-frequency loads
- Observed in the form of an averaged horizontal force similar to a sea current

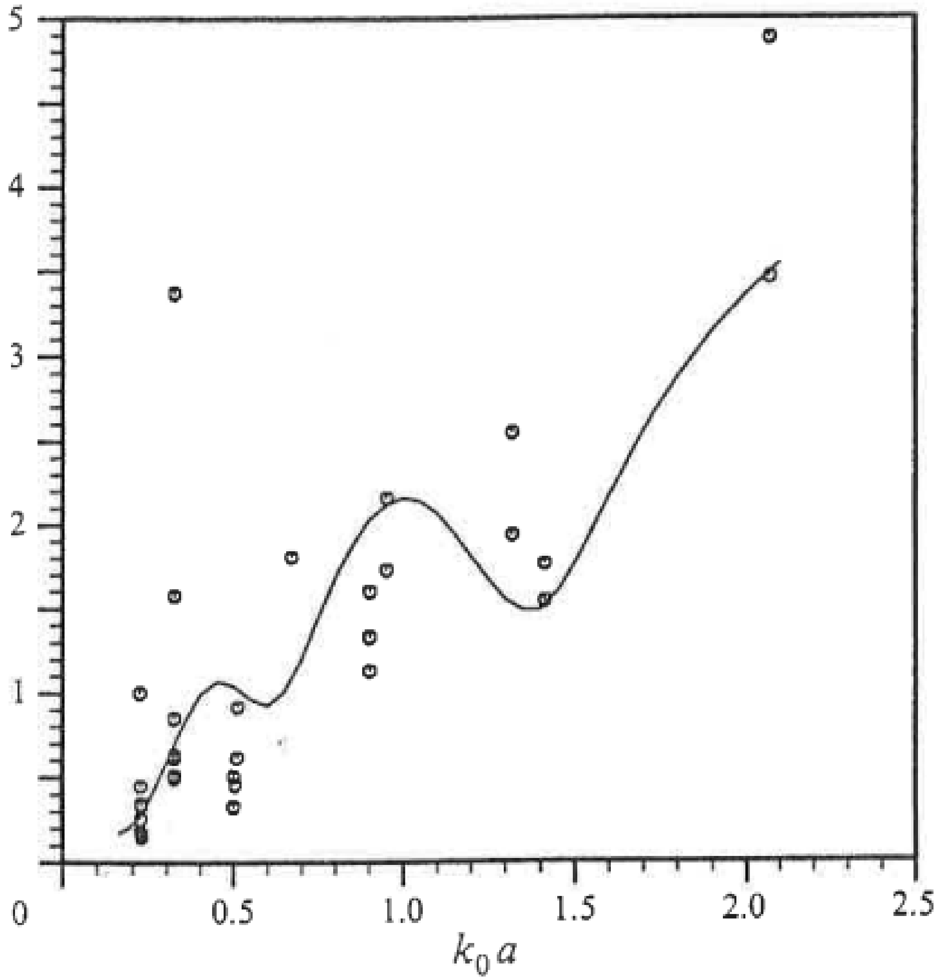


Tension frequency response to irregular sea state, DTU-TLPWT config. WTC1 and WTC4. Hs = 10.74m, Tp = 12.4s

- Deep-water TLPs and gravity-base foundations (GBF) have shown resonant effects in natural period range of 3 - 5 sec
- Observed in basin tests and at sea when sea state peak periods were 3 - 5 times the resonant periods of affected structure
  - Sea state peak period 9 – 15 sec

Ringing (TLP only)

- Highly non-linear, third-order resonant effect
- Strong forces in very short period of time, causing impulse-like excitations
- Sporadic occurrence during extreme sea states, associated with high and steep waves



Modulus of third-harmonic horizontal force divided by ρ g A^3, compared to model test results (Malenica & Molin, 1995)

Y. M. Scolan, M. Le Boulluec, X. B. Chen, G. Deleuil, P. Ferrant, S. Malenica, and B. Molin. Some results from numerical and experimental investigations on the high frequency responses of offshore structures. In 8th International Conference on the Behaviour of Offshore Structures (BOSS), Delft, Netherlands, 1997

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