Ice-capable floating wind turbine structures: Loads assessment of the TetraTLP concept

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Contents

Introduction

Objective

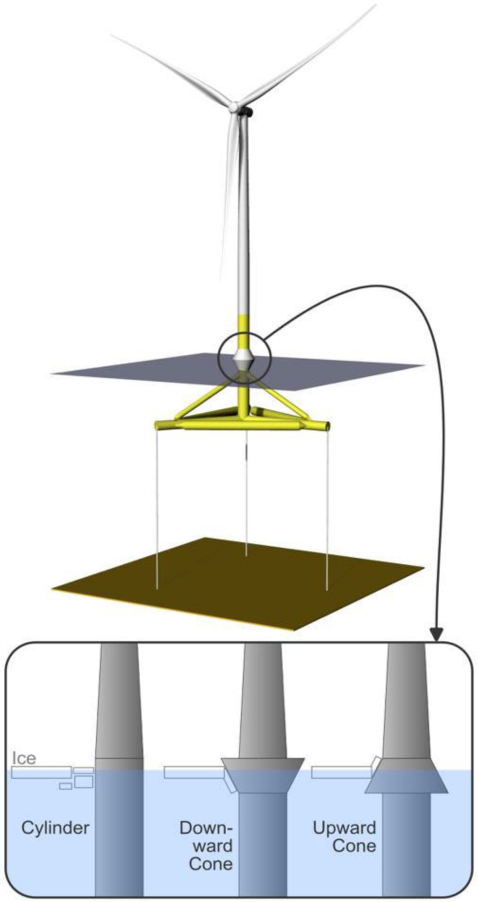
- Design and perform load assessment on FOWT substructure in ice conditions.

Motivation

- Utilization of wind resource in ice prone regions
- 415 GW technical potential for floating wind energy in Great Lakes *[NREL,2022]*

Floater Concept

- TetraTLP fitted with ice cone to mitigate ice loads
- Less developed concept chosen for beneficial dynamic behavior



Source: NREL, *Offshore Wind Energy Technical Potential for the Contiguous United States,* 2022

Literature Review

Standards

- *IEC 61400-3-2 TS:2019, Annex D*
  - Do not use guidelines presented in *IEC 61400-3-1*.
  - Refer to *ISO 19906*.

- *ISO 19906:2019*
  - Presents ice load models developed for bottom fixed structures
  - No specific guidelines for floating structures
  - Proposes use of operational measures
    - Ice management
    - Move-off capability

Literature Review

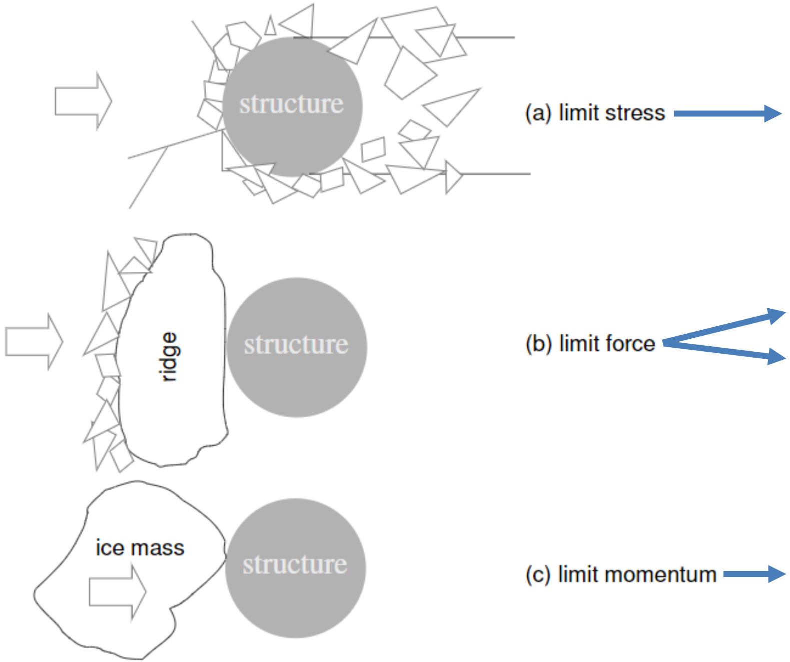
Research

- From oil and gas
    - Focus on **broken ice**

- From wind energy
    - Focus on **bottom fixed** substructures, especially in the Baltic Sea
    - Focus on **vertical** substructures

- Limited research on **conical**, **floating** substructure in **fast ice**

Ice Structure Interaction



Limit states

Ice is broken in interaction with structure

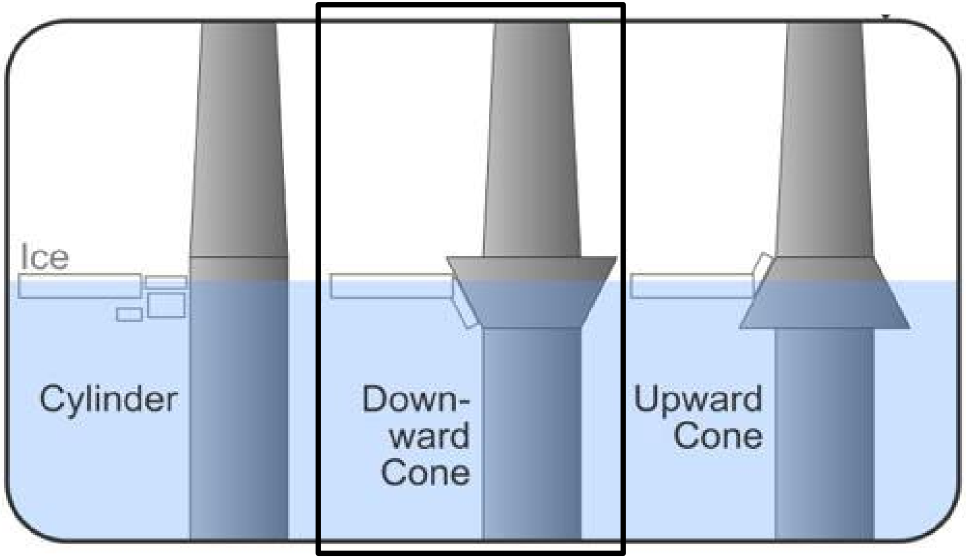
Limited driving force on ice cover

Ice breaks away from structure

Finite ice feature is stopped by interaction with structure

Source: Palmer and Croasdale, *Arctic Offshore Engineering,* 2013

Ice Structure Interaction



Ice breaks in crushing

F_{ice} >

Ice breaks in bending

Ice submerged

F_{ice} <

Ice lifted

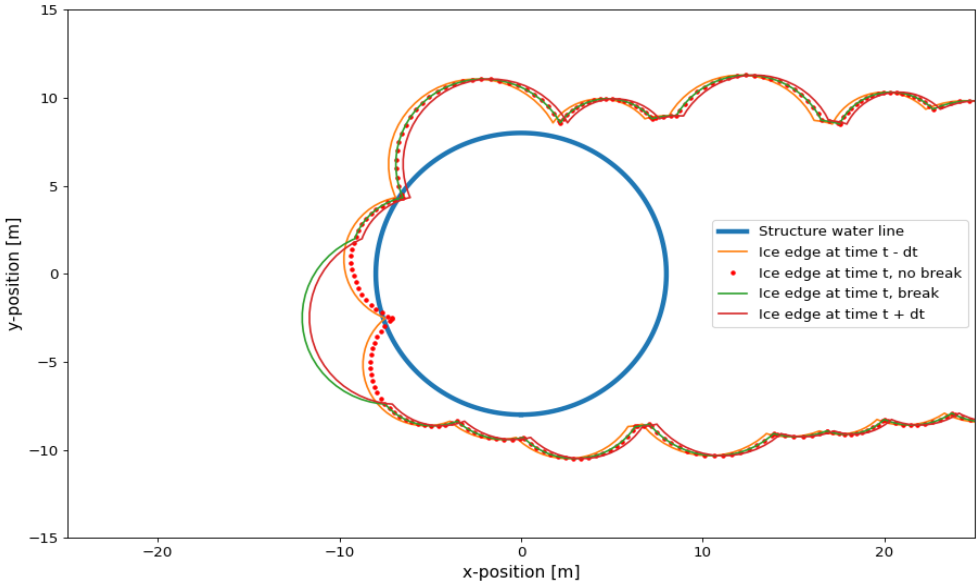
Integrated Load Analysis

Ice Load Model

- External function developed for OrcaFlex
- For each time step
  - Compute quasi-static ice load from contact area and contact pressure
  - Compare vertical force to load bearing limit, P_f *[Kerr, 1975]*

$$P_f = \frac{1}{0.966}\left(\frac{\theta}{\pi}\right)^2 \sigma_f h_i^2$$

  - Remove ice wedge if load bearing limit is exceeded
- Only considers load required to break ice
  - Disregards ice rubble
- Validation performed against various model scale data. Will be discussed in conference paper



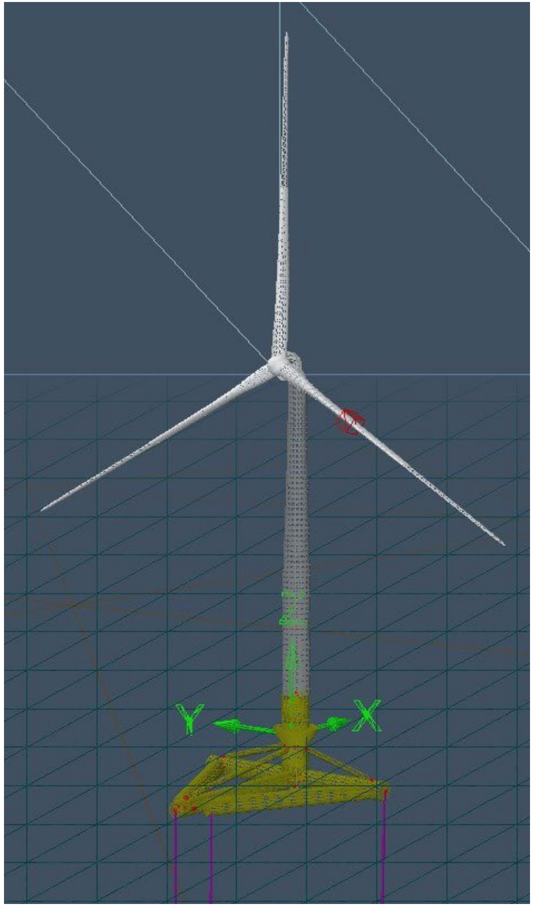
Source: Kerr, *THE BEARING CAPACITY OF FLOATING ICE PLATES SUBJECTED TO STATIC OR QUASI-STATIC LOADS - A Critical Survey*, 1975

Integrated Load Analysis

OrcaFlex Model

- IEA 15MW Offshore Reference Wind Turbine
  - Increased tower stiffness to reduce pitch natural period
- Displacement: 12000 ton
- Draft: 20 m

- Preliminary ice cone design defined considering trade-off between wave and ice loads
- Ice cone properties:
  - Angle: 60º
  - Length: 6 m
  - Material: Steel

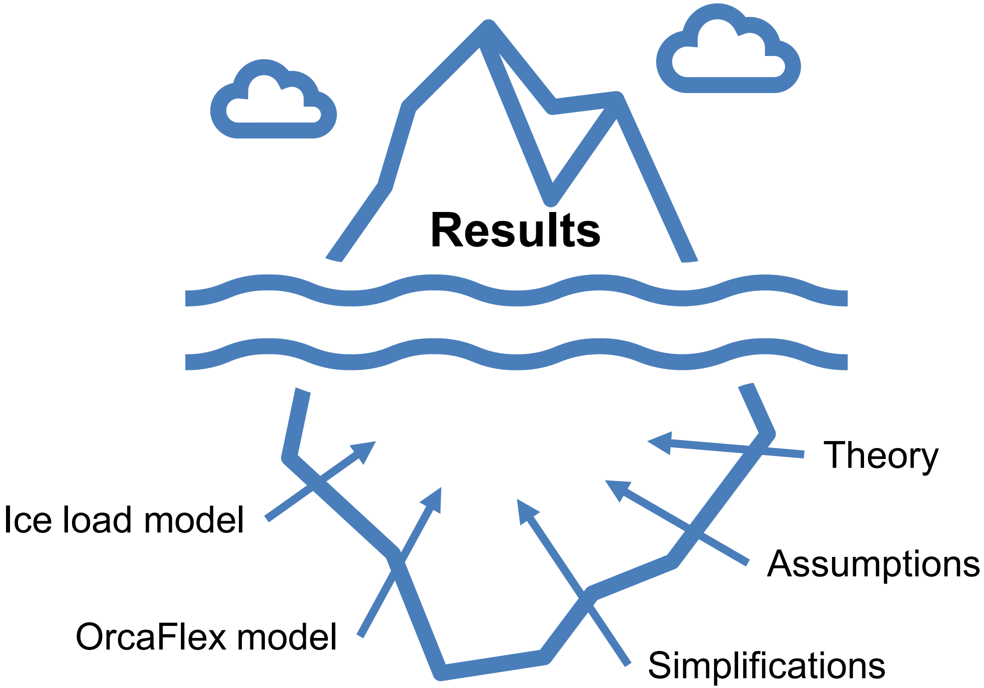


Integrated Load Analysis

Design Load Cases

- From IEC 61400-3-1
- One wind direction considered
- No wind-ice misalignment considered
- Ice velocity estimated as 1% of wind speed at hub height

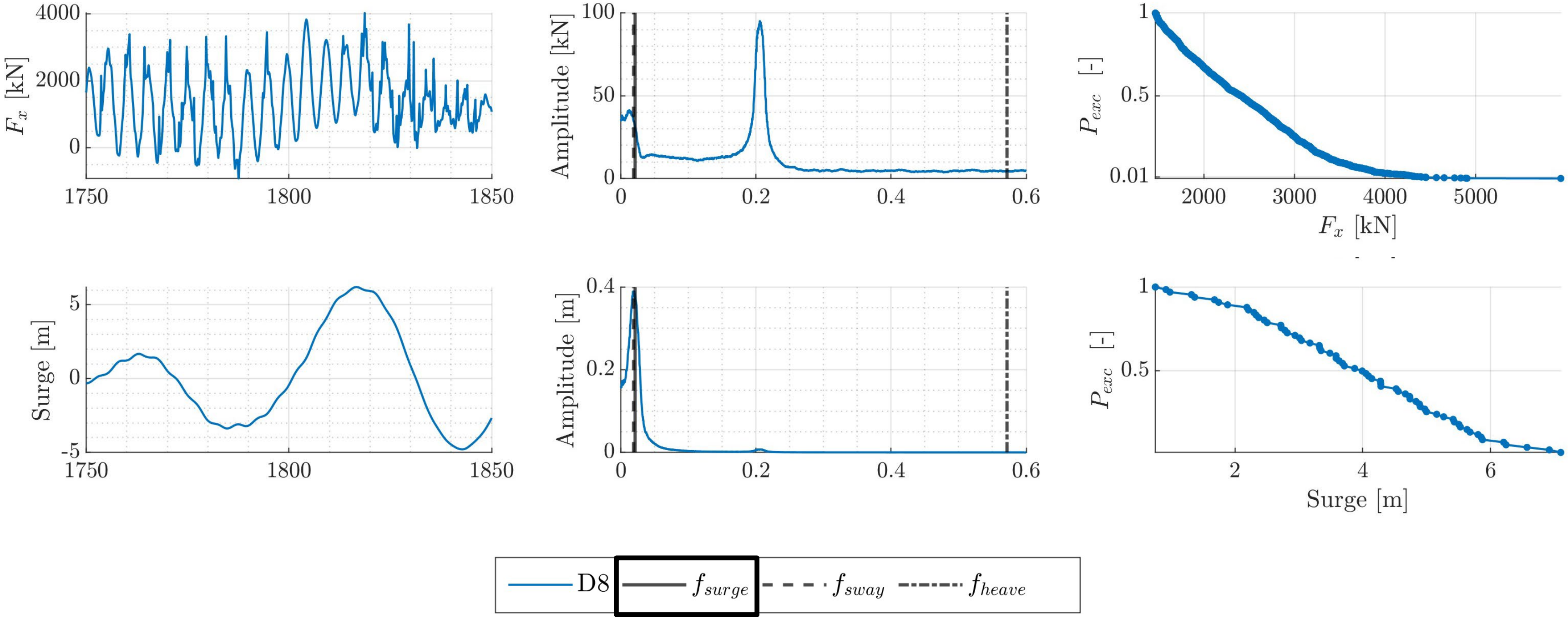
Design Situation	DLC	Ice Condition	Type
Power Production	D1	Horizontal ice load from temperature fluctuations	U
	D2	Horizontal load from water level fluctuations or arch effects	U
	D3	**Horizontal load from moving ice at relevant velocities**	**U**
	D4	Horizontal load from moving ice at relevant velocities	F
	D5	Vertical load from fast ice cover due to water level fluctuations	U
Parked	D6	Pressure from ice ridges	U
	D7	Horizontal load from moving ice at relevant velocities	F
	D8	**Horizontal load from moving ice at relevant velocities**	**U**


Results
Theory
Ice load model
Assumptions
OrcaFlex model
Simplifications

Results

Displacements - F_x

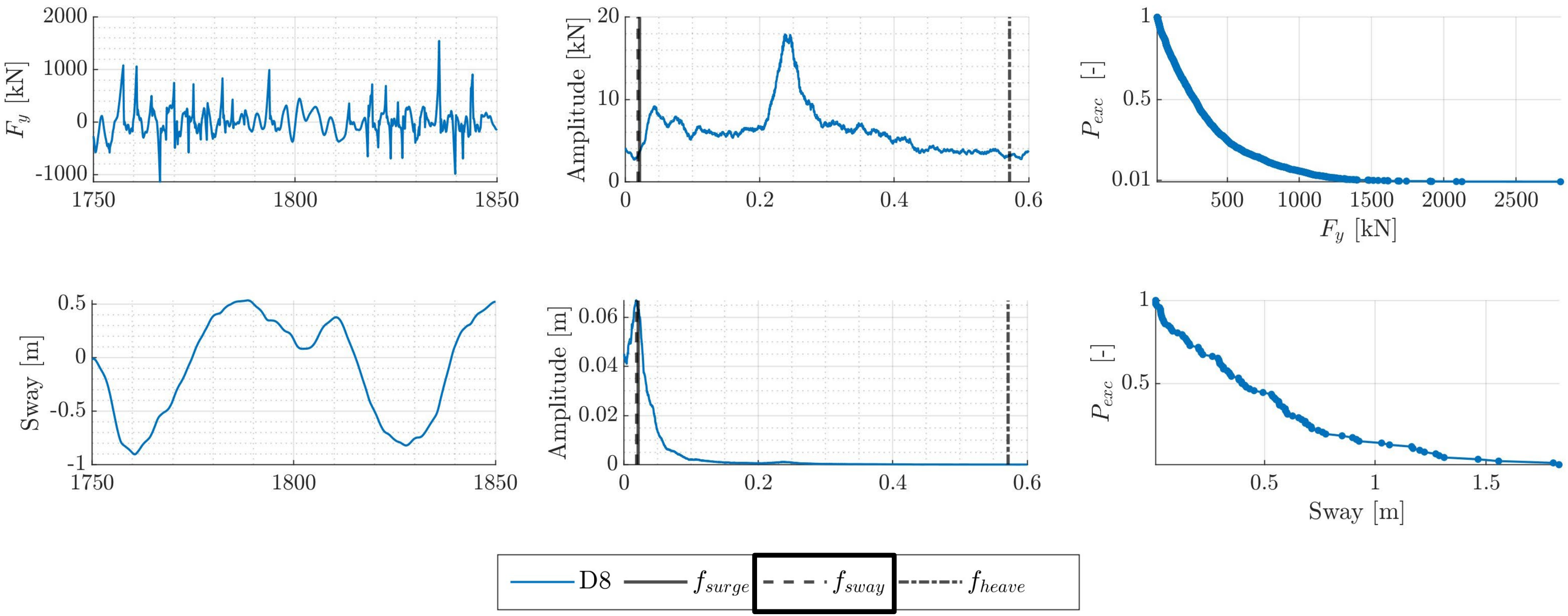
Significant coupling with f_{surge}



Results

Displacements - F_y

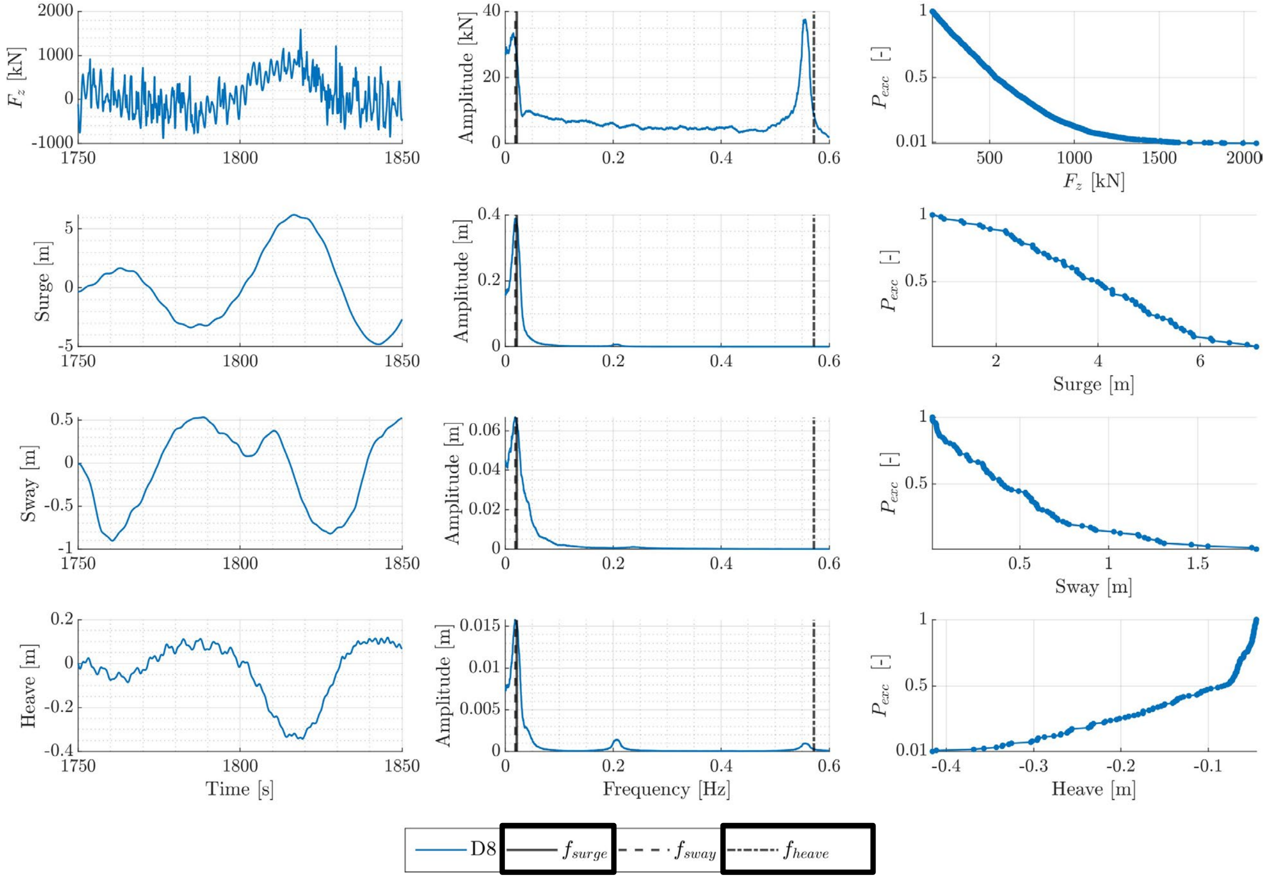
Significant coupling with $2 \cdot f_{sway}$ (+ harmonics)



Results

Displacements - F_z

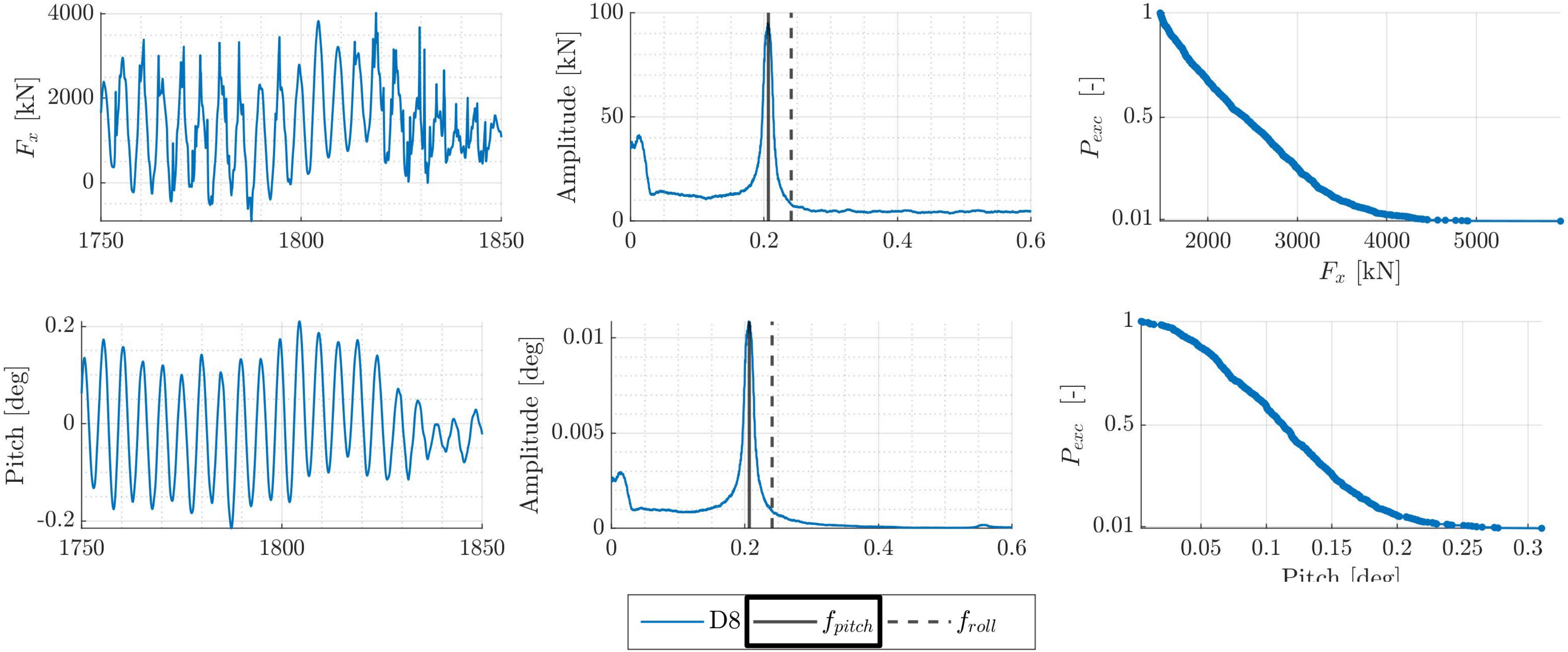
Significant coupling with f_{surge} and f_{heave}



Results

Rotations - F_x

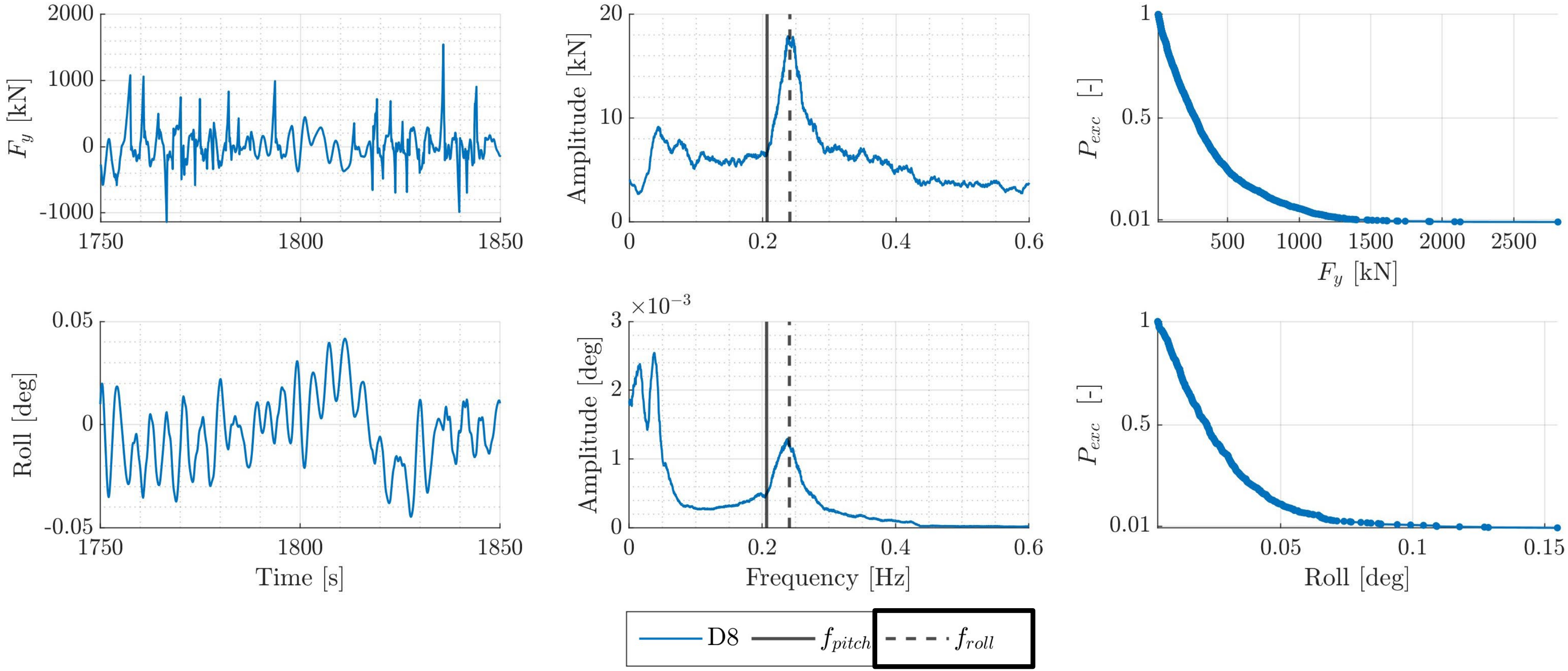
Strong coupling with f_{pitch}



Results

Rotations - F_y

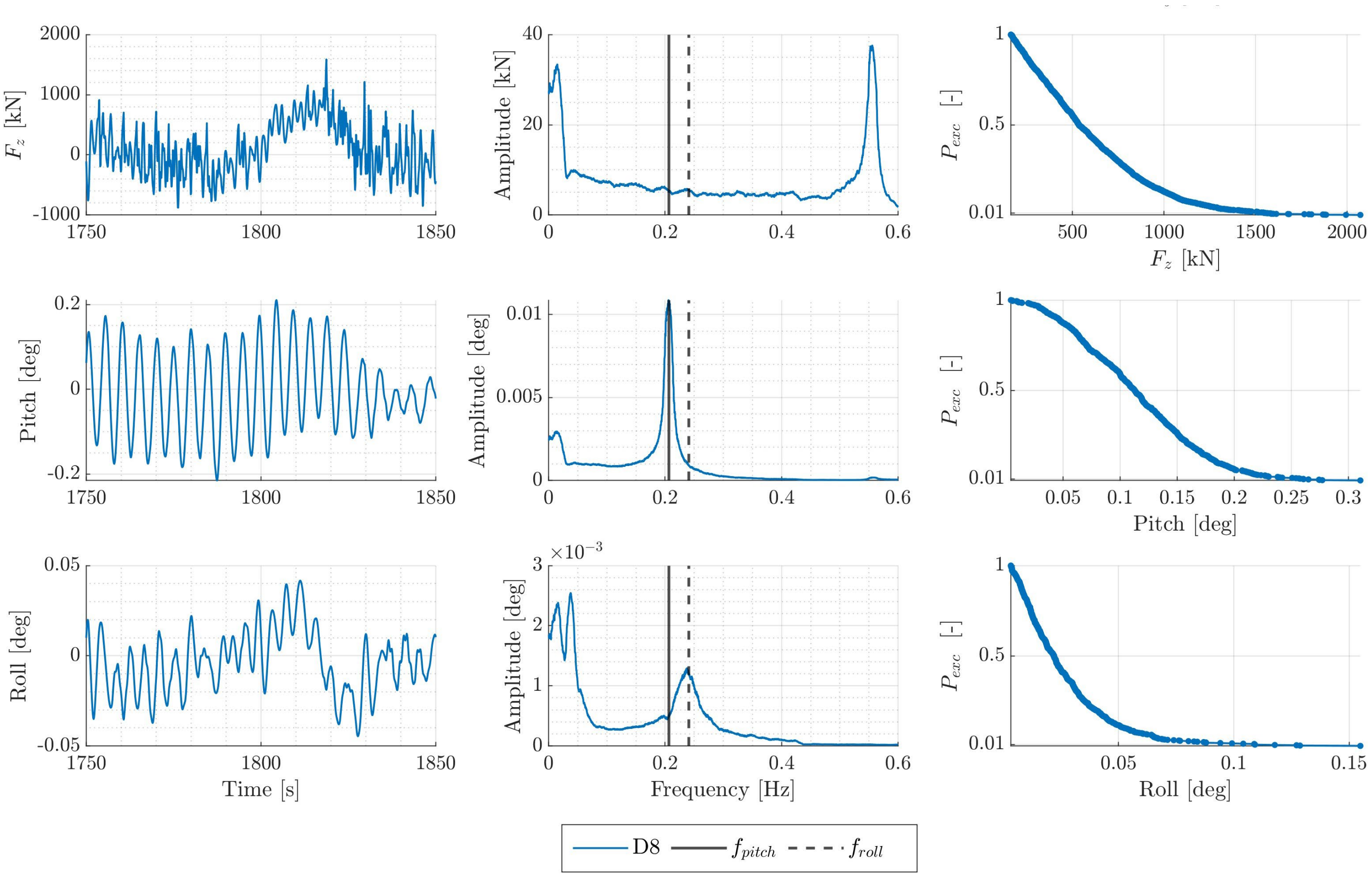
Strong coupling with f_{roll}



Results

Rotations - F_z

No coupling with natural frequency of rotational DOFs



Results

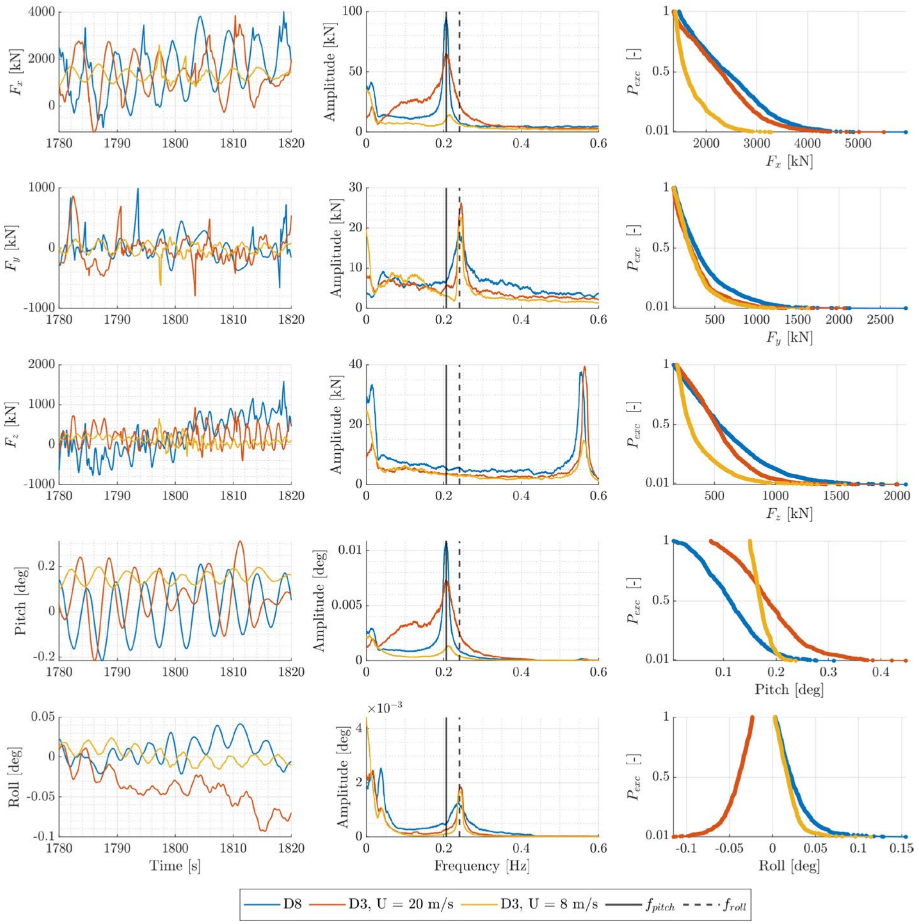
Aerodynamic Damping

- Three levels
  - **No** aerodynamic damping
    (D8, $U_{150\ m} = 45.6\ m/s$)
  - **Negative** aerodynamic damping
    (D3, $U_{150\ m} = 20\ m/s$)
  - **Positive** aerodynamic damping
    (D3, $U_{150\ m} = 8\ m/s$)

- Changes from differences in ice velocity
  - F_y not affected by aerodynamic damping, only experiences minor changes

- **Aerodynamic damping found to significantly decrease, F_x and F_z**

- Negative damping found to experience oscillations at lower frequencies
  - Believed to be caused by controller de-tuning



Conclusion

- Ice load model has been developed

- FOWT substructure has been designed
  - TetraTLP with an ice cone

- The global response of the system has been studied
  - Significant couplings were found between the ice load and the dynamic response
    - Especially rotational degrees of freedom

  - Aerodynamic damping was found to significantly decrease the ice load resulting from the coupling with the pitch natural frequency

Thanks for your attention

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