Technical University of Denmark

Experimental study of the DTU 10 MW wind turbine on a TLP floater in waves and wind

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Part of the INNWIND.EU project

Scaling principles

Preliminary results
Extreme environment

Aerodynamic design

Preliminary results
Gentle environment

Floater design

Setup and validation

Scaling principles for floating wind turbine tests I

Define a length scale ratio

$$\lambda = \frac{L_p}{L_m}$$

Gravity is dominant!
Ratio of force to gravity is preserved

$$\frac{M_p a_p}{M_p g} = \frac{M_m a_m}{M_m g} \quad \Rightarrow \quad a_p = a_m$$

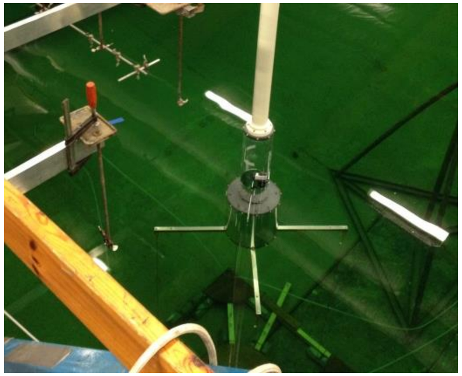
Hereby time scale ratio is locked:

$$\frac{T_p}{T_m} = \sqrt{\lambda} \quad \Leftarrow \quad \frac{L_p}{T_P^2} = \frac{L_m}{T_m^2}$$

Preserve ratio of structural and fluid mass

$$\frac{M_p}{\rho_{wp}\mathrm{Vol}_p} = \frac{M_m}{\rho_{wm}\mathrm{Vol}_m} \quad \Rightarrow \quad \frac{M_p}{M_m} = \frac{\rho_{wp}}{\rho_{wm}}\lambda^3$$

Classical Froude scaling of mass, length and time.
Well known for wave tank tests.



Scaling of rotor properties

Froude scaling of hydrodynamics: $\lambda = \frac{L_p}{L_m}$ $\quad \frac{T_p}{T_m} = \sqrt{\lambda}$ $\quad \frac{M_p}{M_m} = \frac{\rho_{wp}}{\rho_{wm}} \lambda^3$

Keep overall geometry

$$R_{rotor,m} = R_{rotor,p} / \lambda$$

Keep consistent scaling of rotational frequency

$$\omega_m = \omega_p / \sqrt{\lambda}$$

Preserve tip speed ratio

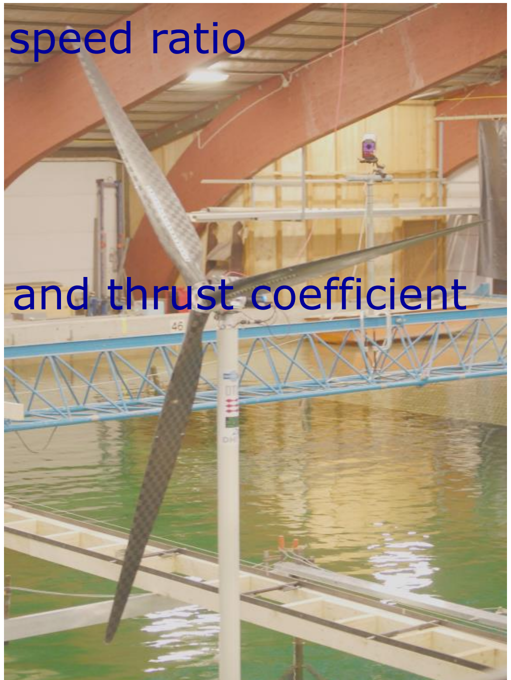
$$\frac{\mathrm{TSR}_p}{\mathrm{TSR}_m} = \frac{\omega_p R_p}{u_{ap}} \frac{u_{am}}{\omega_m R_m} = 1$$

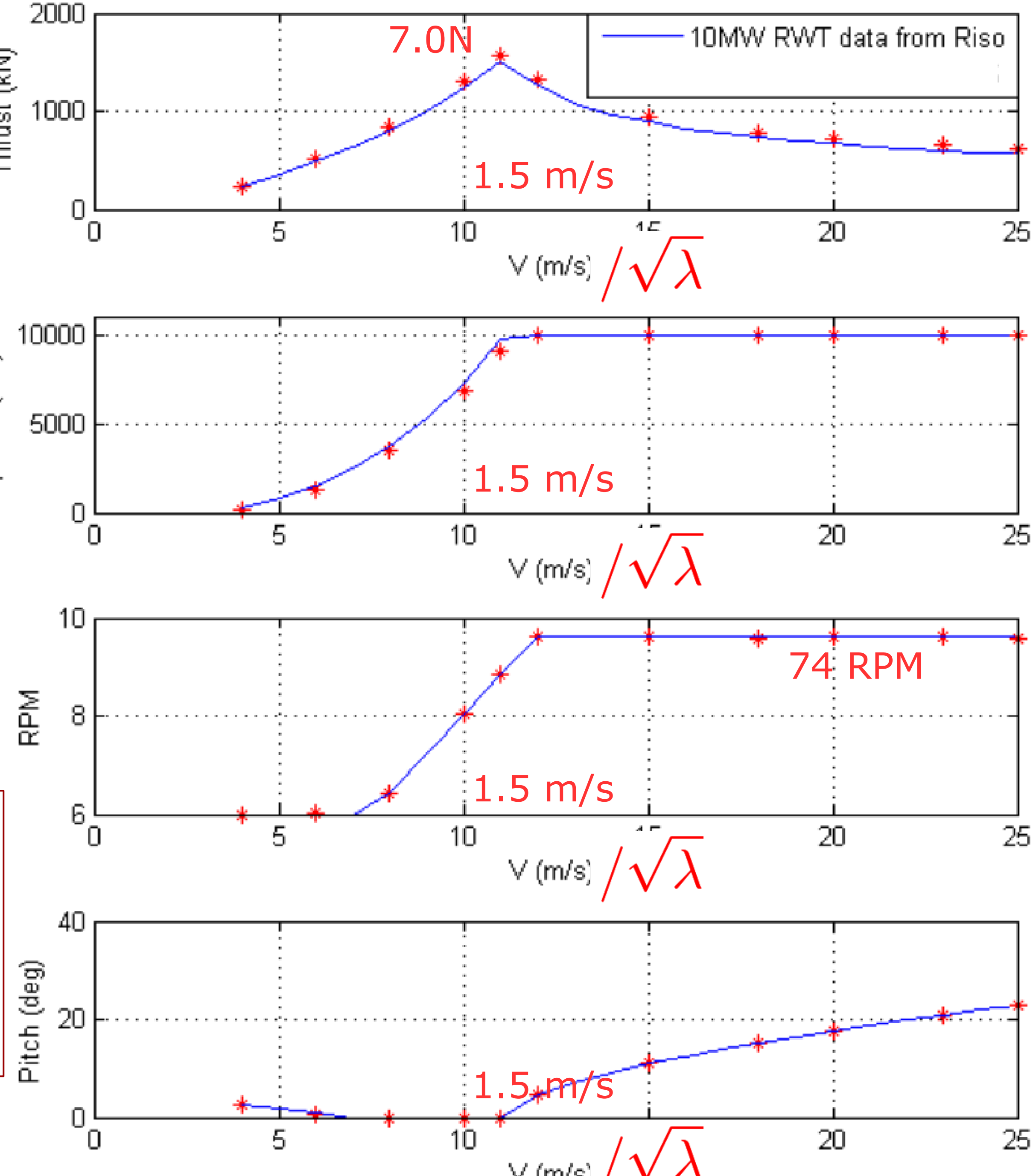
$$\Rightarrow \quad u_{a,m} = u_{a,p} / \sqrt{\lambda}$$

Thrust force and thrust coefficient

$$F_T = \rho_a C_T A u_a^2 \sim \rho_w \lambda^3$$

$$\Rightarrow \quad \frac{C_{Tp}}{C_{Tm}} = \frac{\rho_{wp}}{\rho_{wm}}$$





Air velocities (model scale) ~ 1.5 m/s

Re (proto scale) ~ 10M

Re (model scale): ~ 25k

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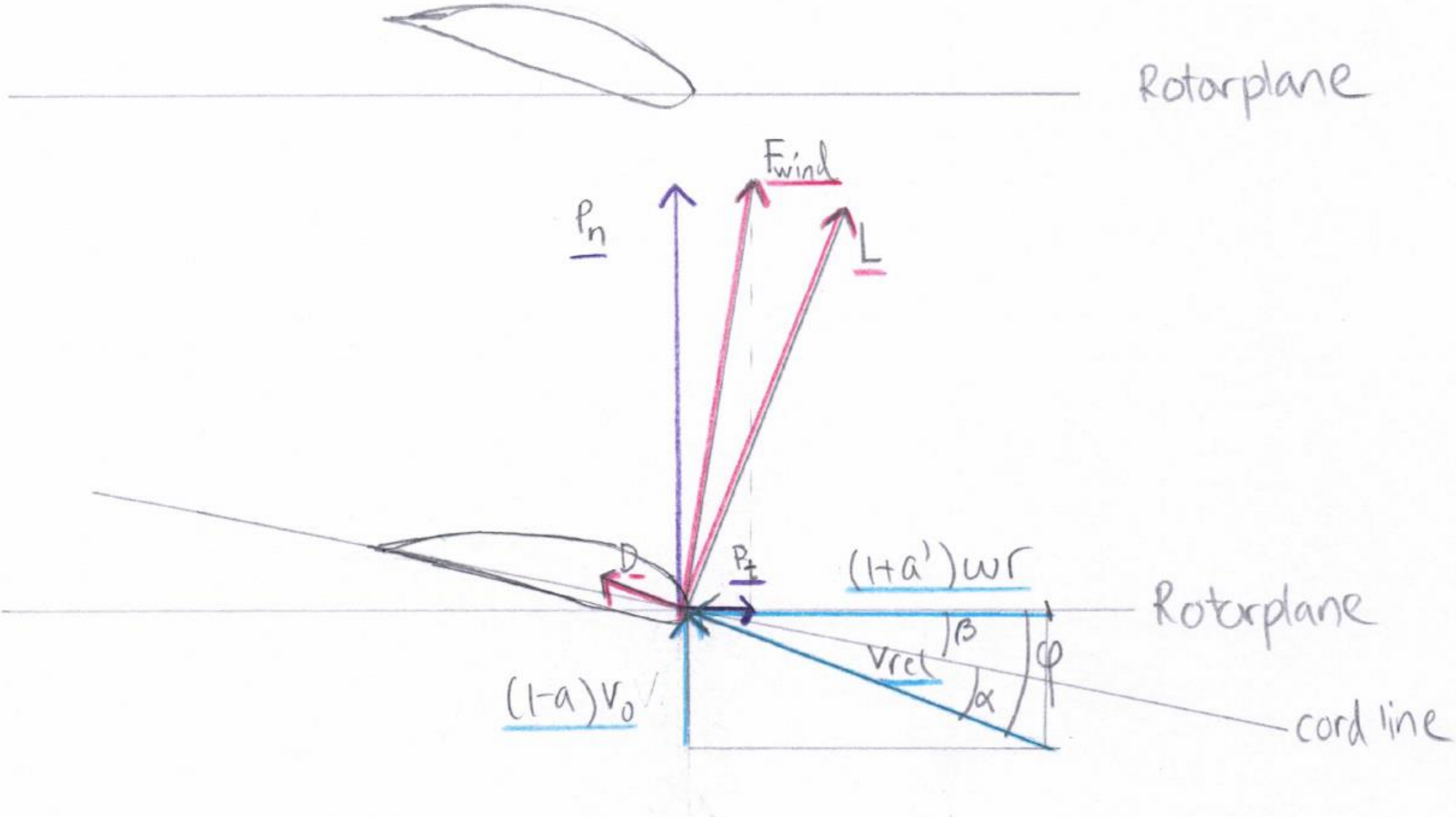
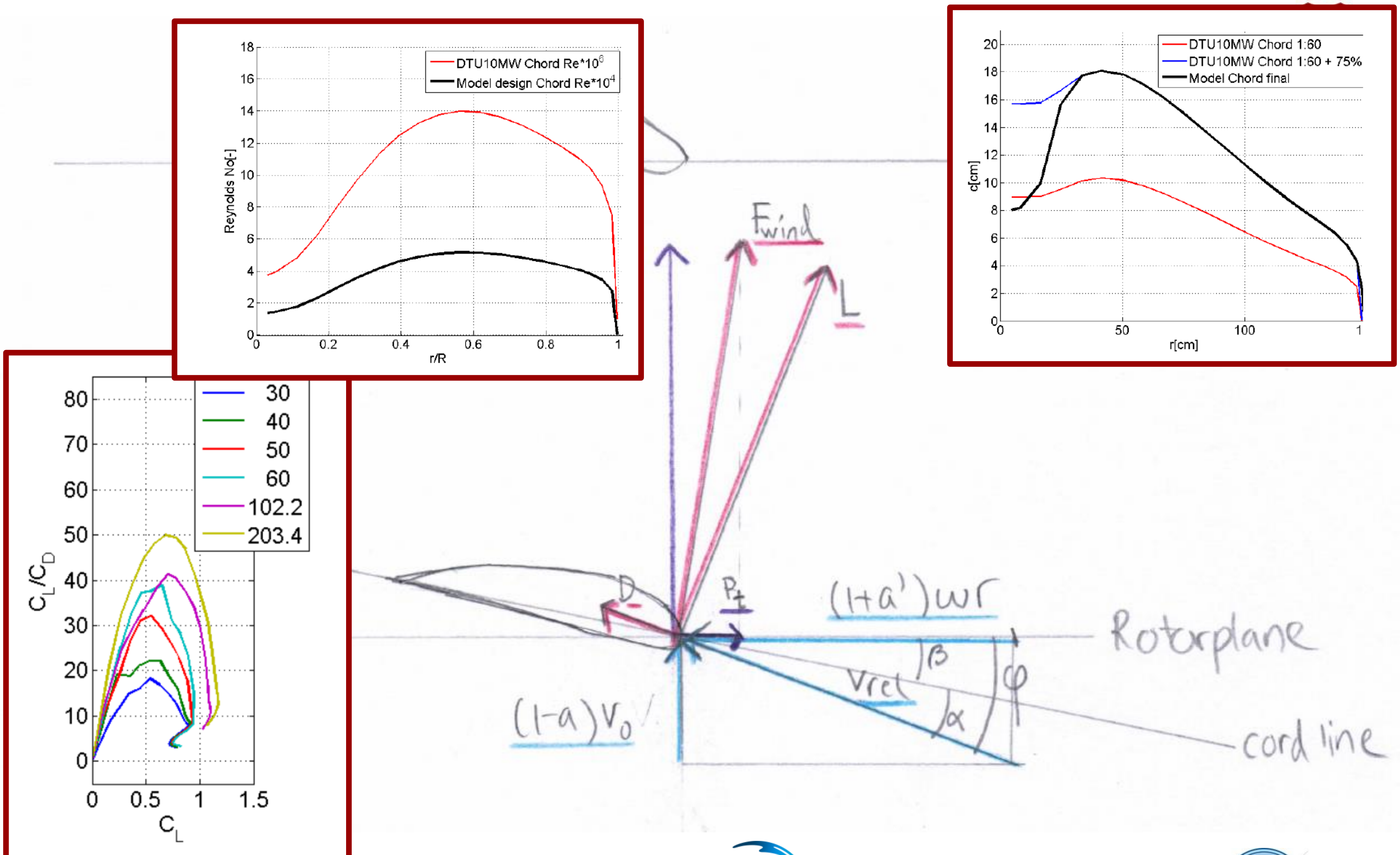


Aerodynamic design



Low-Re airfoils and 2D wind tunnel measurements

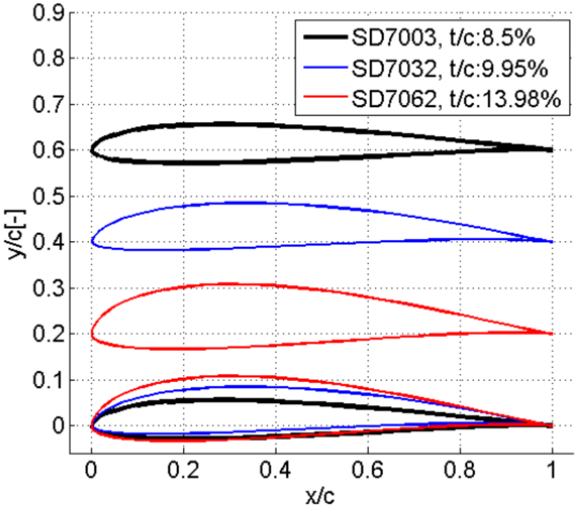


Figure 5 Applied airfoils for spanwise sections.

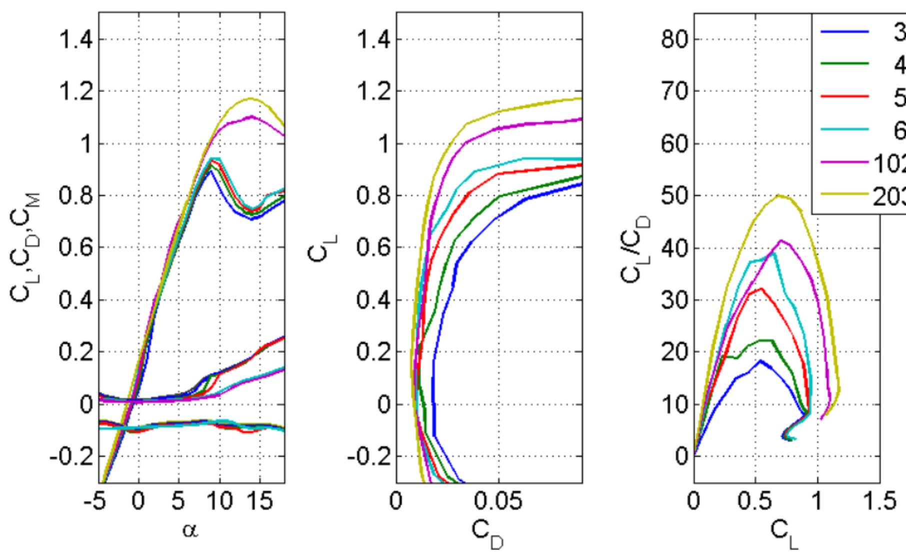


Figure 3 Measured airfoil characteristics for SD7003 at Reynolds number 30k, 40k, 50k, 60, 100k, 200k. Selig data applied for 100k and 200k.

Mold for blades

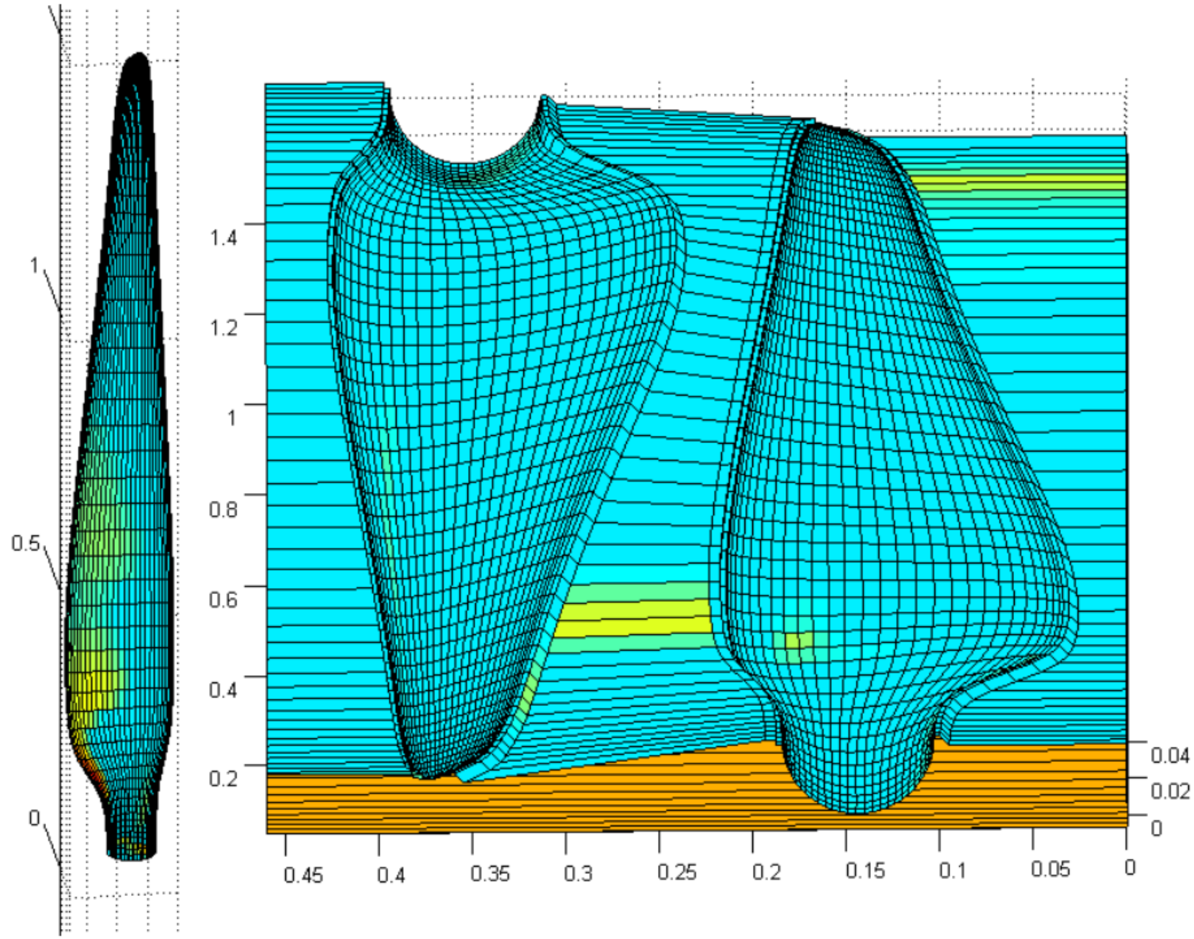
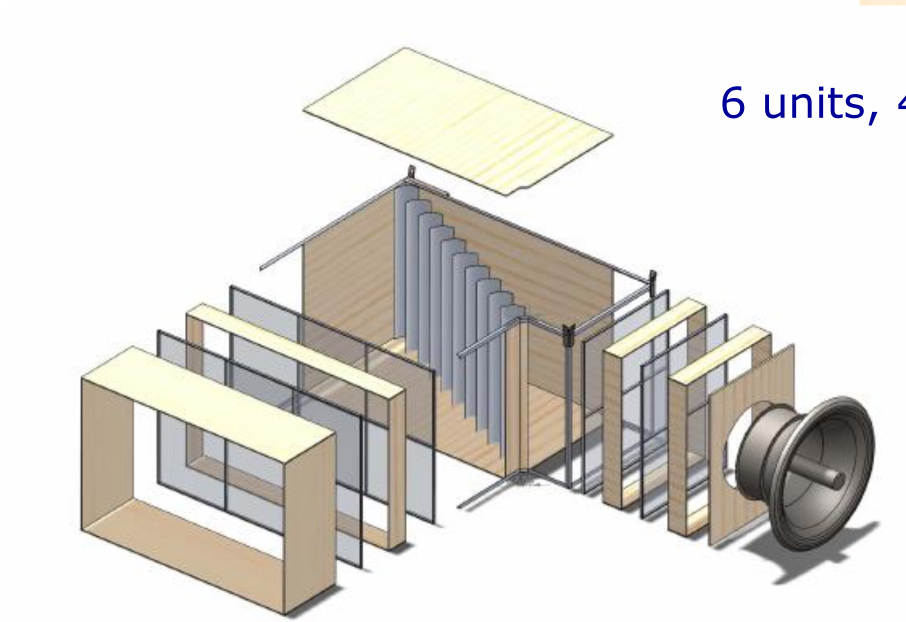
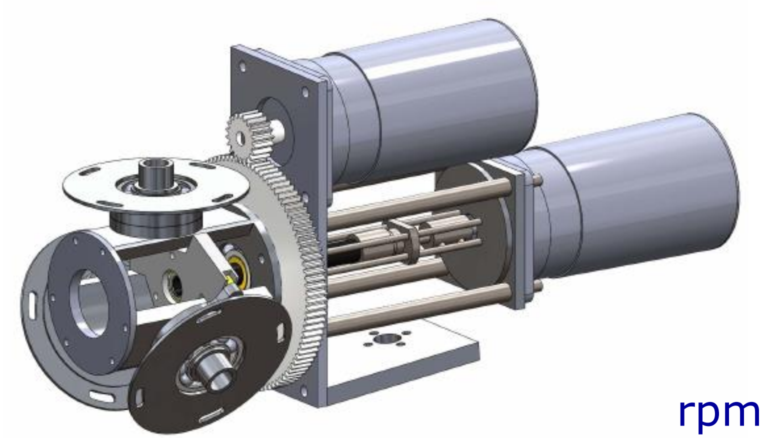


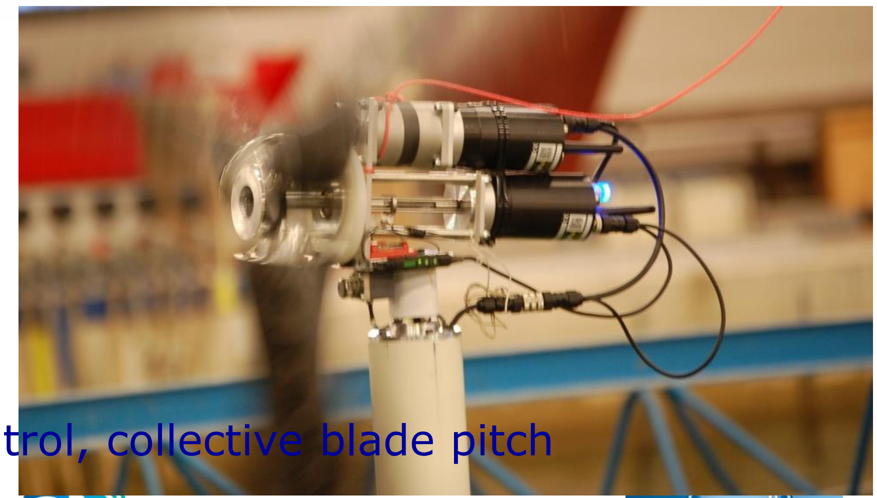
Figure 10 Model scale wind turbine blade (left) and negative mold (right)

Wind generator and hub



6 units, 4x4m, max speed of 1.7 m/s





rpm control, collective blade pitch

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(model scale) ~ 1.5 m/s

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Re (model scale): ~ 25k

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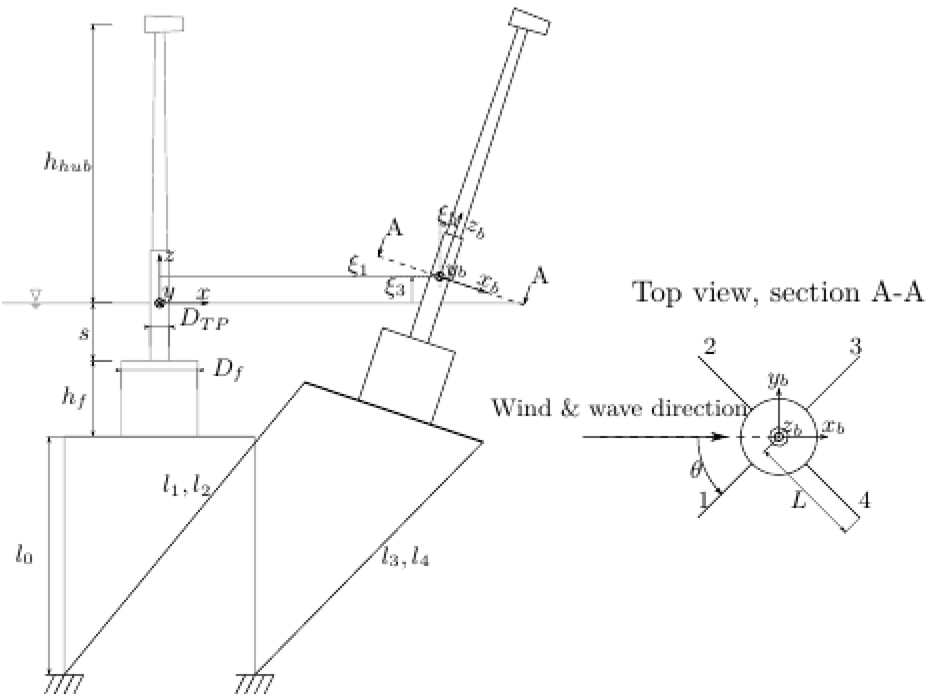
Compact, cost efficient

TLP was chosen – Bachynski (2014) gives input on design considerations

Designed with static model and a WAMIT based dynamic model



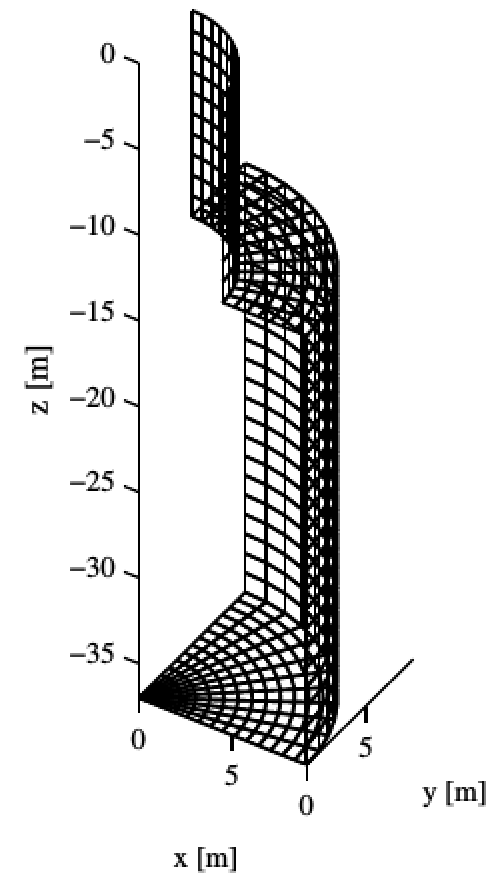
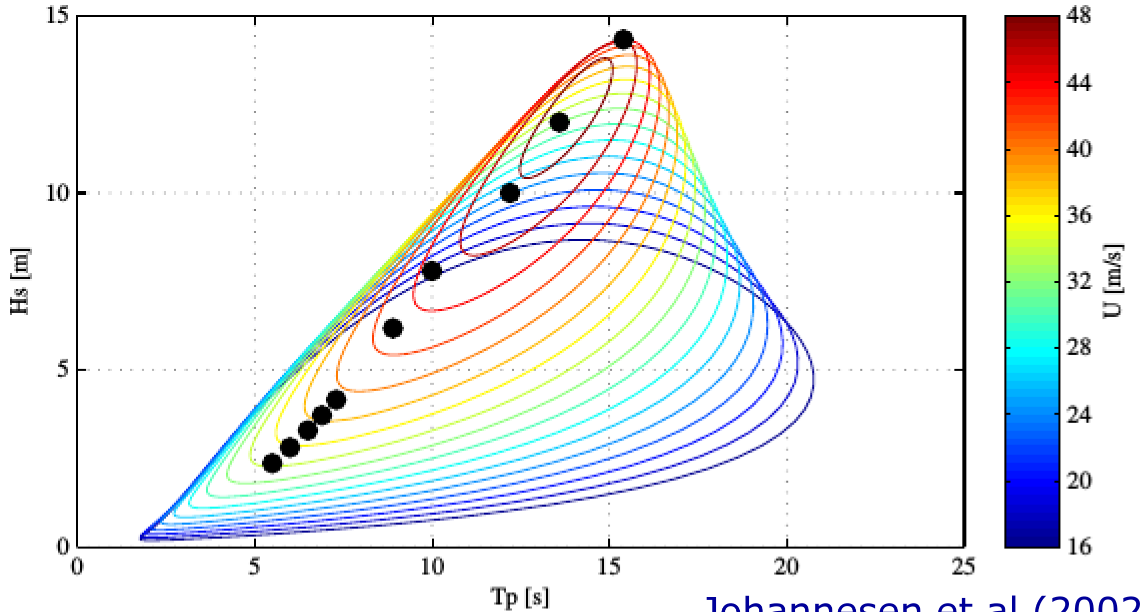


Figure 2.4: Floater geometry loaded into WAMIT.

Environmental conditions

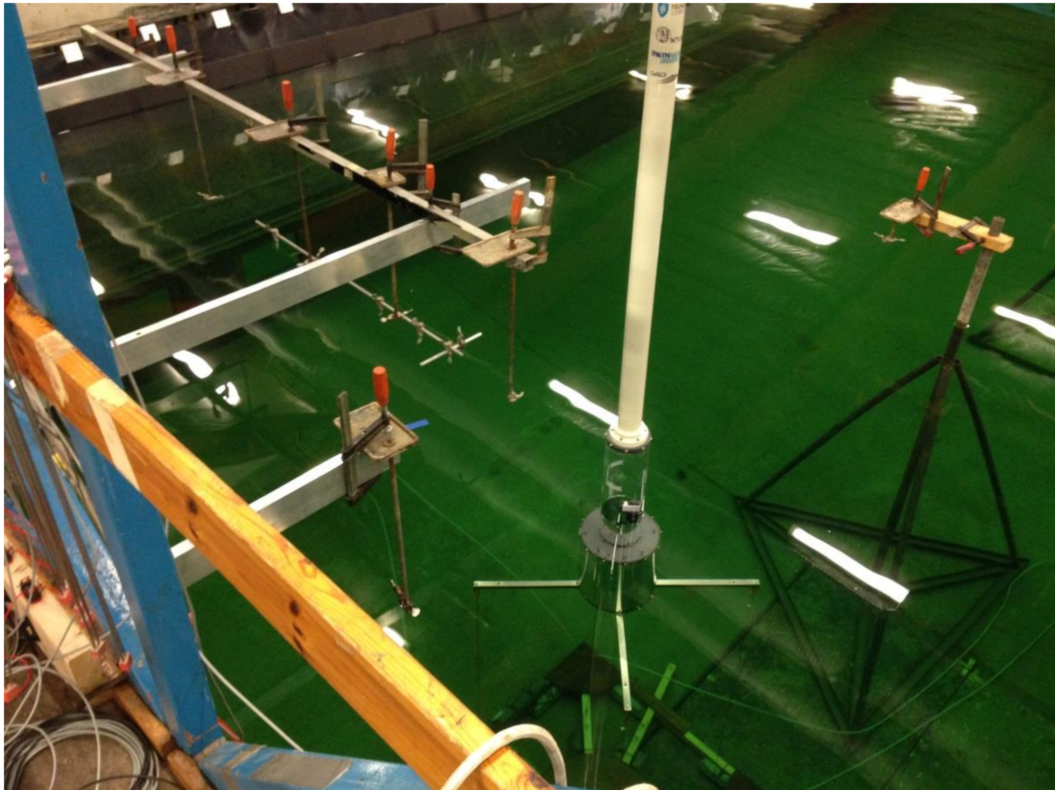


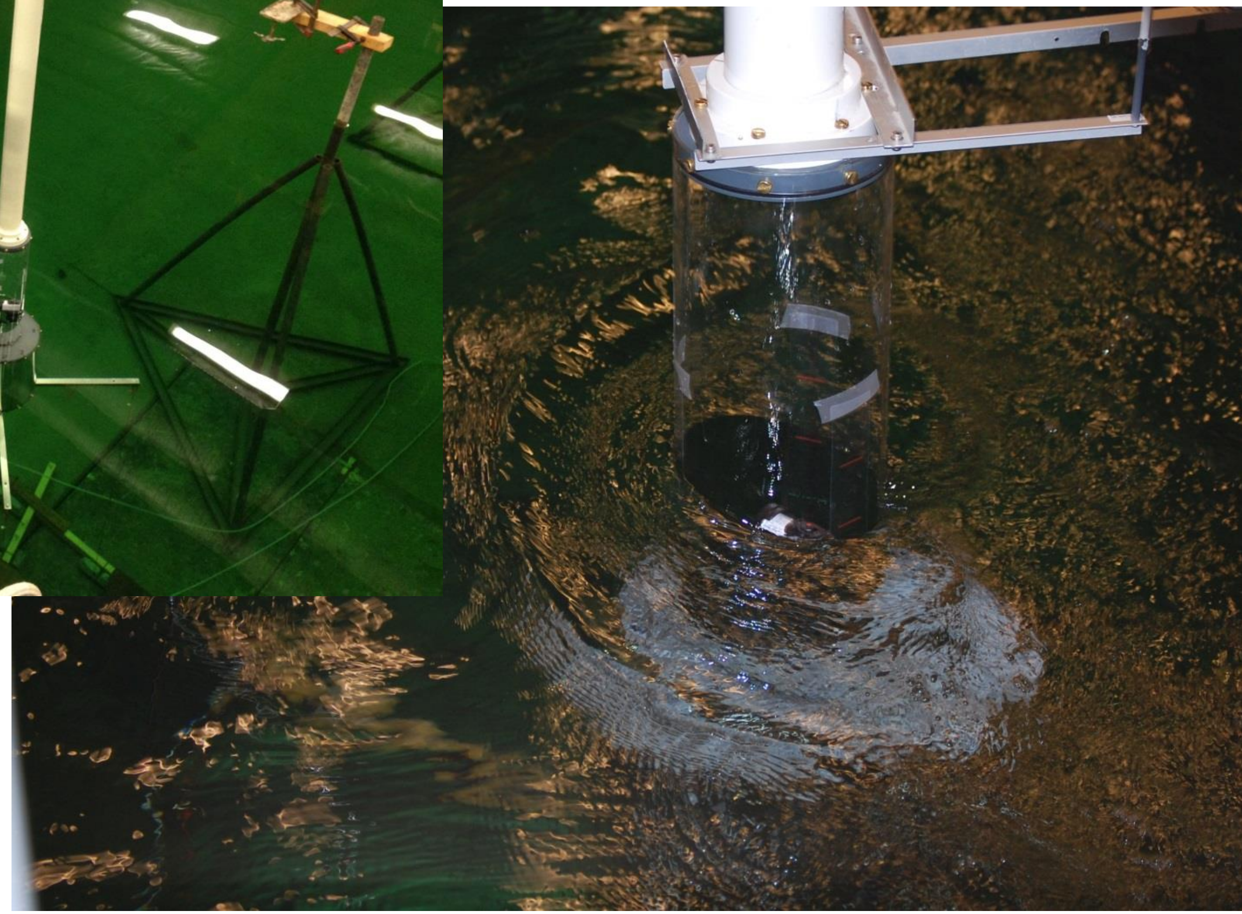
Johannesen et al (2002); Bachynski (2014)

Design requirements

max tendon angle with vertical: 10 deg
max tension: 1.8 x T_0
min tension: 0.2 x T_0

The floater





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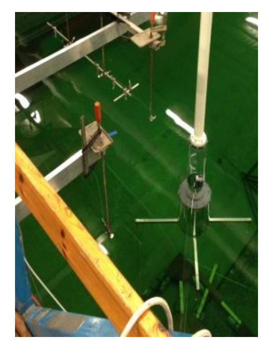
Floater design



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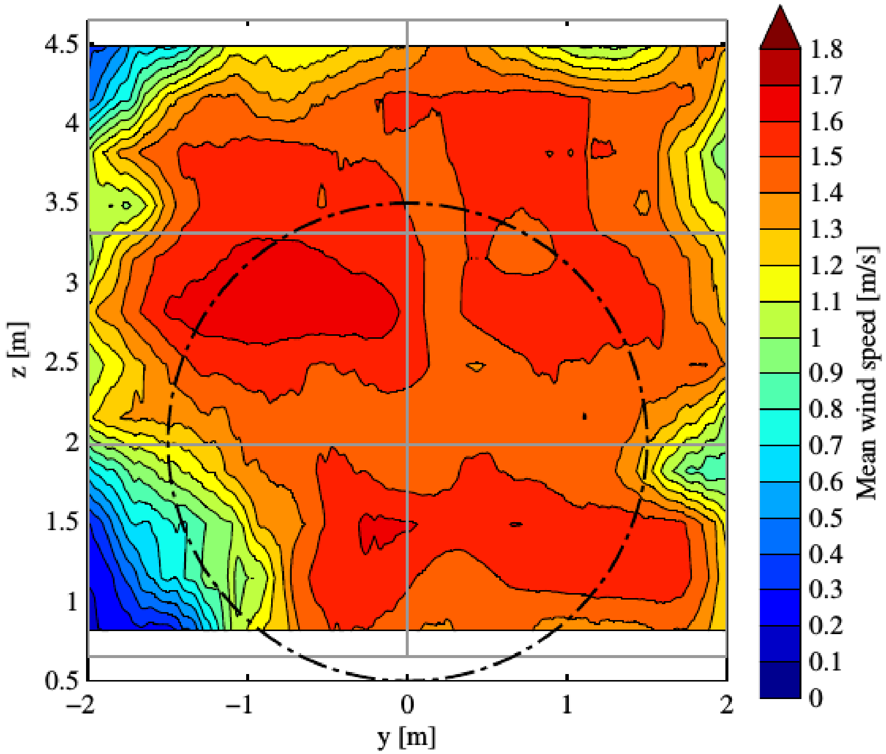
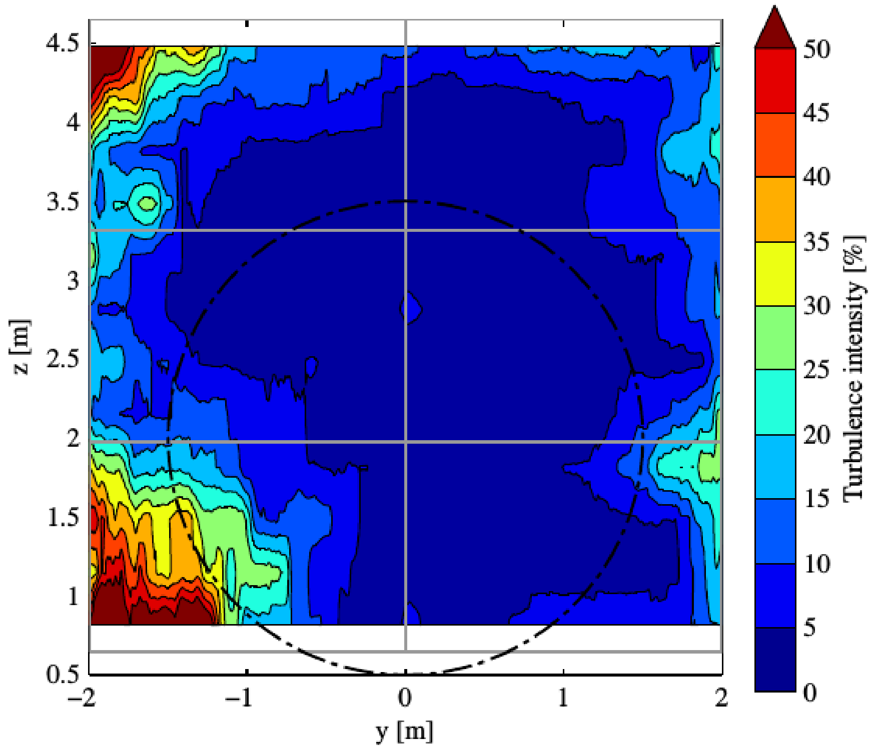
Wind field in rotor plane

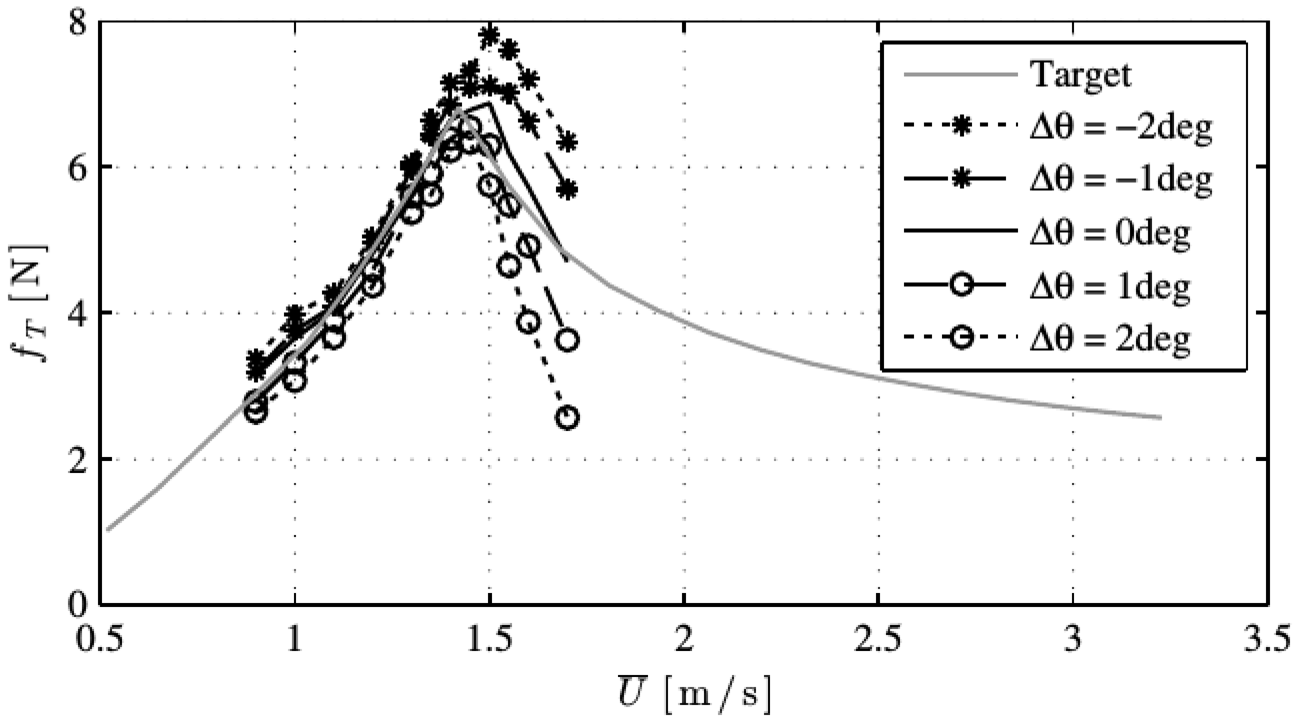


(a) Mean wind speed.



(b) Turbulence intensity.

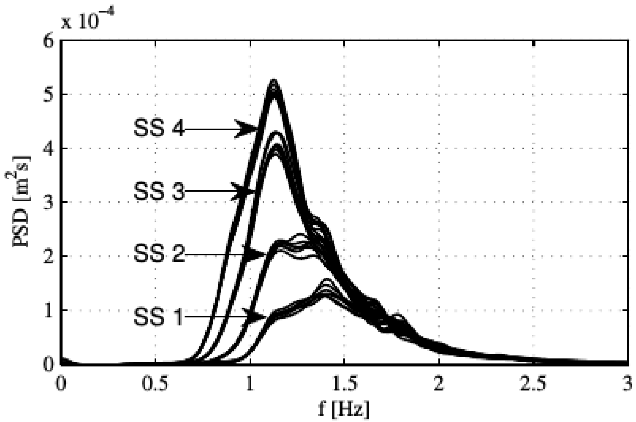
Rotor thrust



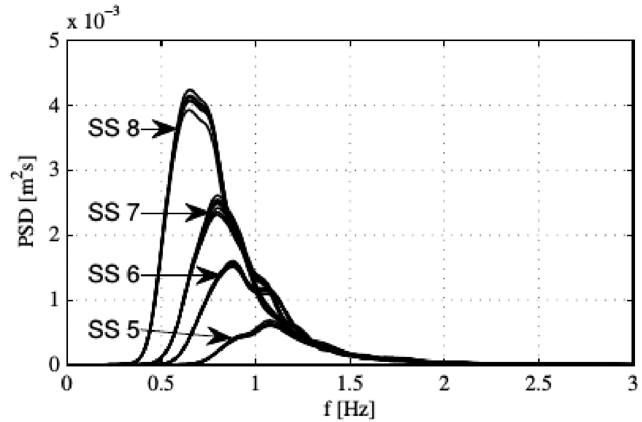
(b) With vortex generators

Figure 5.13: Thrust curves for the wind turbine model

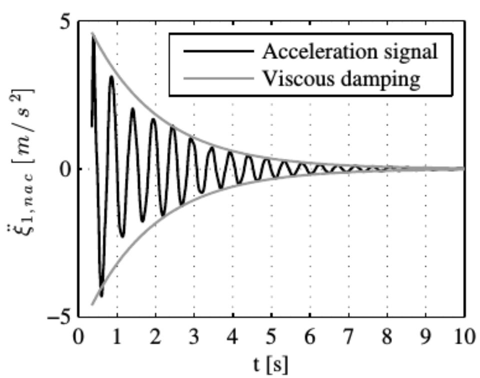
Wave climates and RAOs



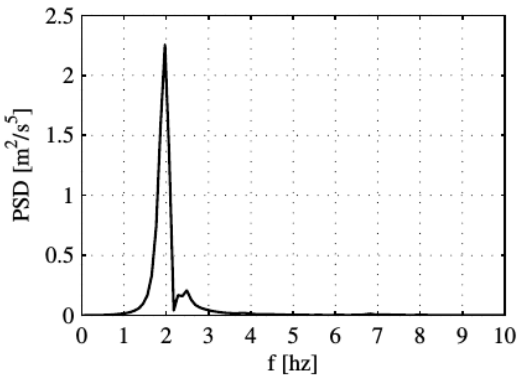
(a) Sea states I01 - I04



(b) Sea states I05 - I08



(a) Acceleration measured in nacelle and decaying amplitude of linear response.



(b) Power spectrum of acceleration signal.

Preliminary results
Extreme environment

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Gentle environment

Scaling principles

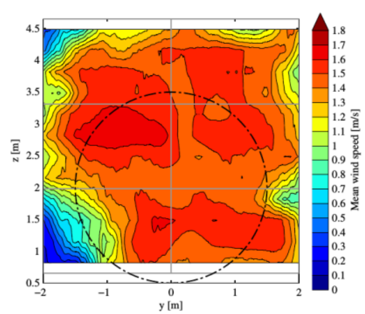
Air velocities
(model scale) ~ 1.5 m/s

Re (proto scale) ~ 10M

Re (model scale): ~ 25k

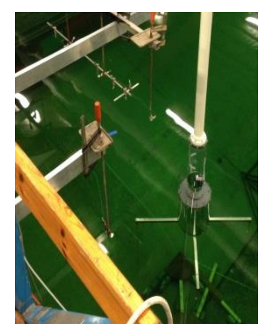
Aerodynamic design

Setup and validation



(a) Mean wind speed.

Floater design



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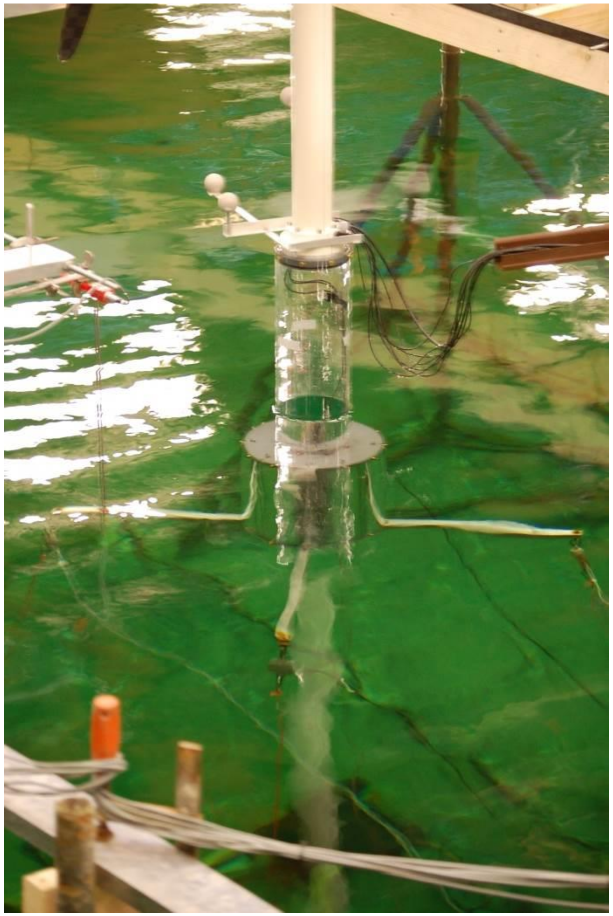
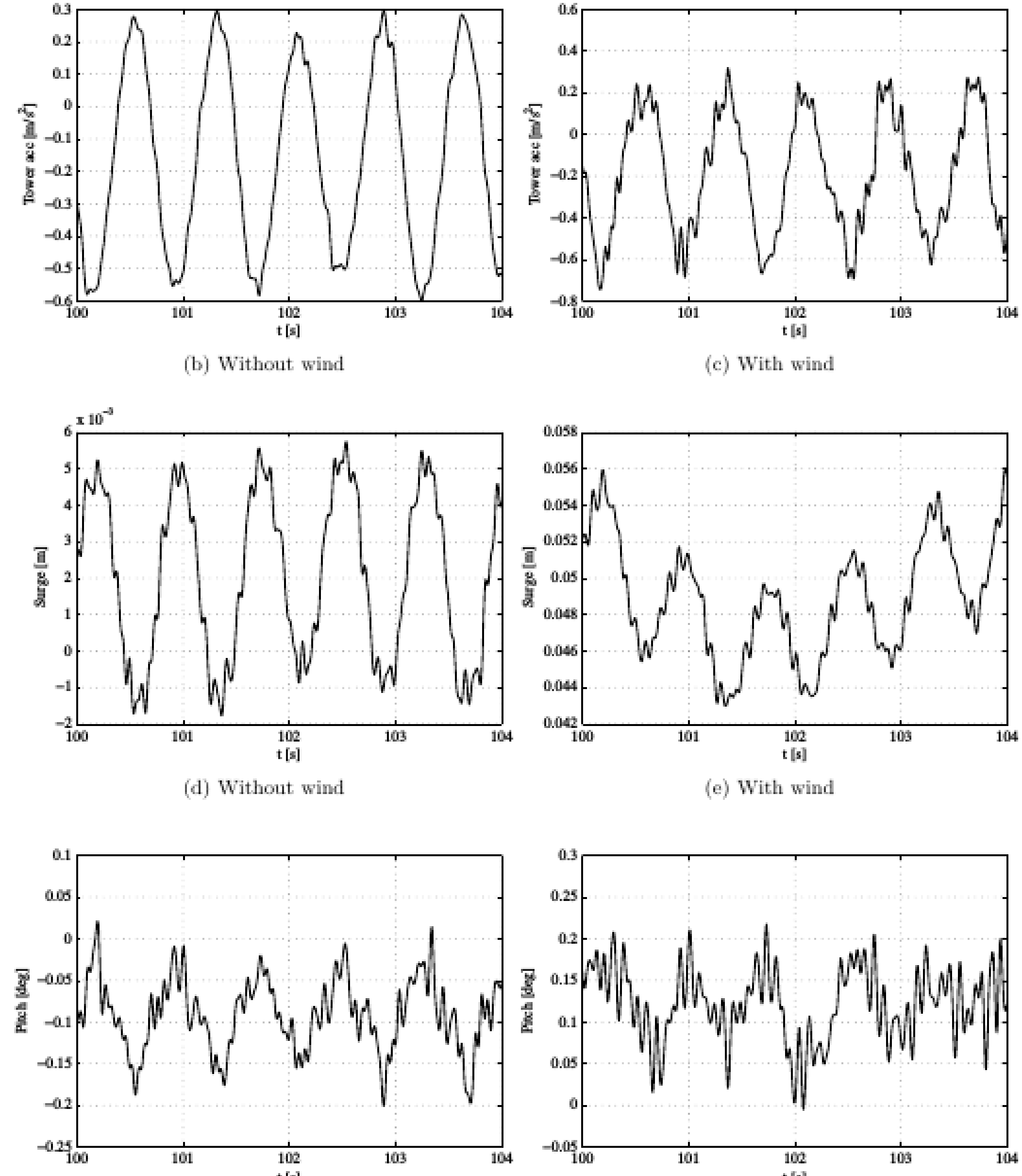
Preliminary results

Regular, gentle waves





(b) Without wind (c) With wind

(d) Without wind (e) With wind

(f) Without wind (g) With wind

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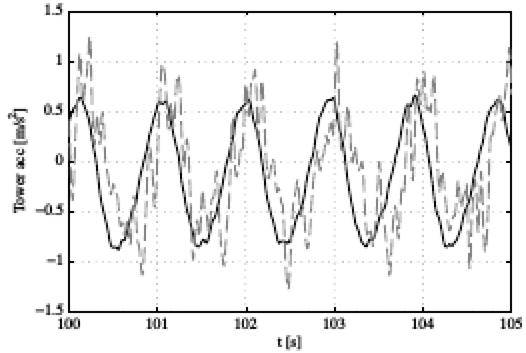
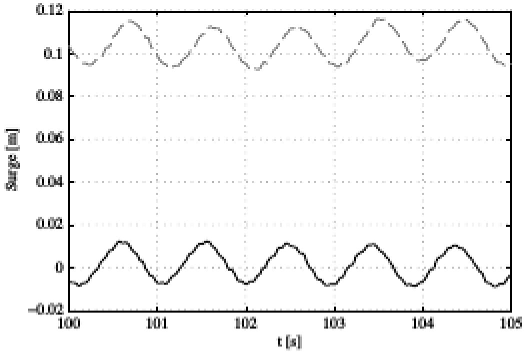
Figure 7.2: Sea state 2

Preliminary results

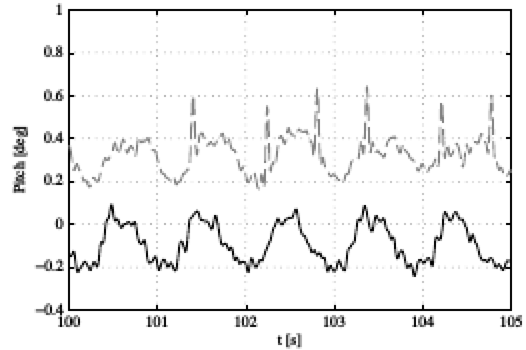
Irregular waves close to
rated wind speed
with and without wind



(a) Tower acc. Seastate 5



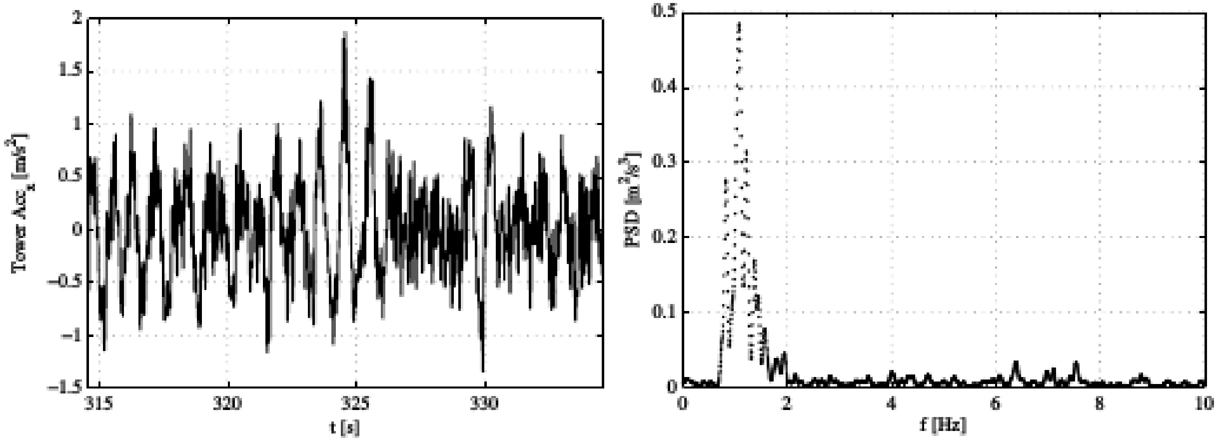
(c) Surge - Seastate 5



(e) Pitch - Seastate 5

Preliminary results

Irregular waves at close to rated wind speed



(a) Time series (b) Spectral analysis

Figure 7.26: Tower acceleration - Seastate 5 - Wind

Preliminary results
Extreme environment

Scaling principles

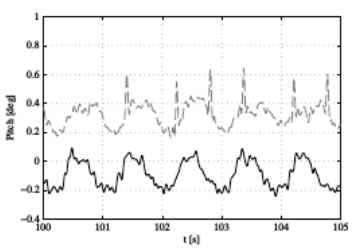
Air velocities
(model scale) ~ 1.5 m/s

Re (proto scale) ~ 10M

Re (model scale): ~ 25k

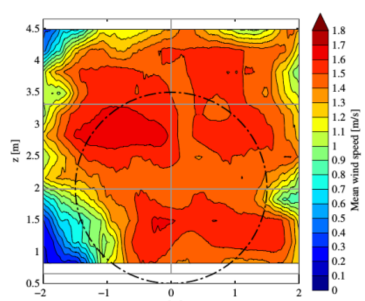
Aerodynamic design

Preliminary results
Gentle environment



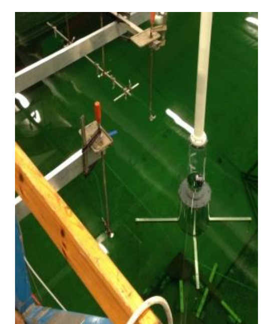
(e) Pitch - Seastate 5

Setup and validation



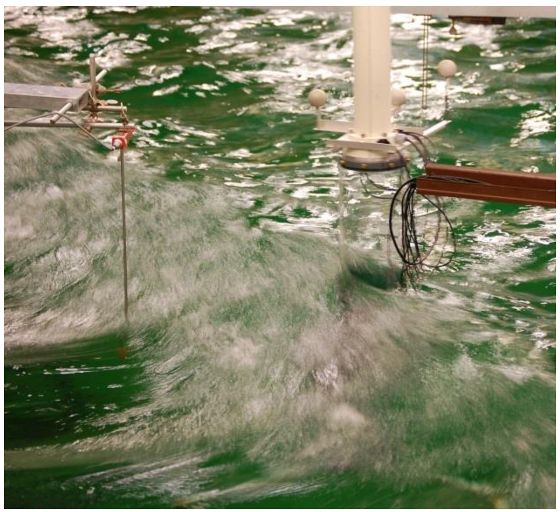
(a) Mean wind speed.

Floater design



Preliminary results

Response to extreme focused wave



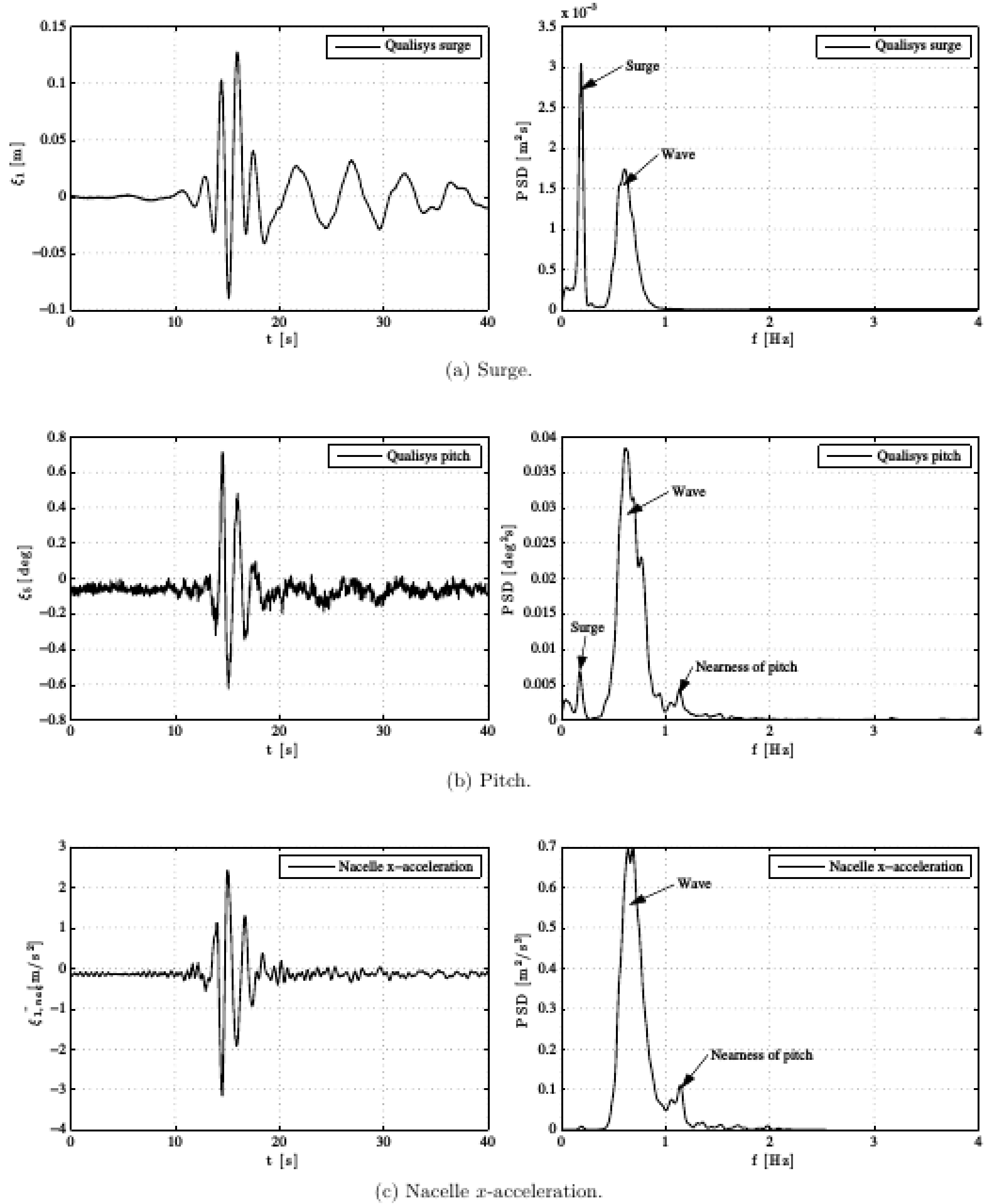
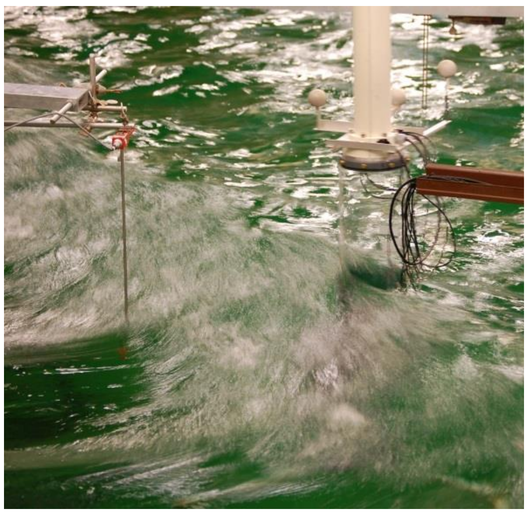


Figure 7.37: Response of structure 1 to focused wave number 8 without wind (S1F08).

Preliminary results

Response to extreme focused wave
Tendon tension



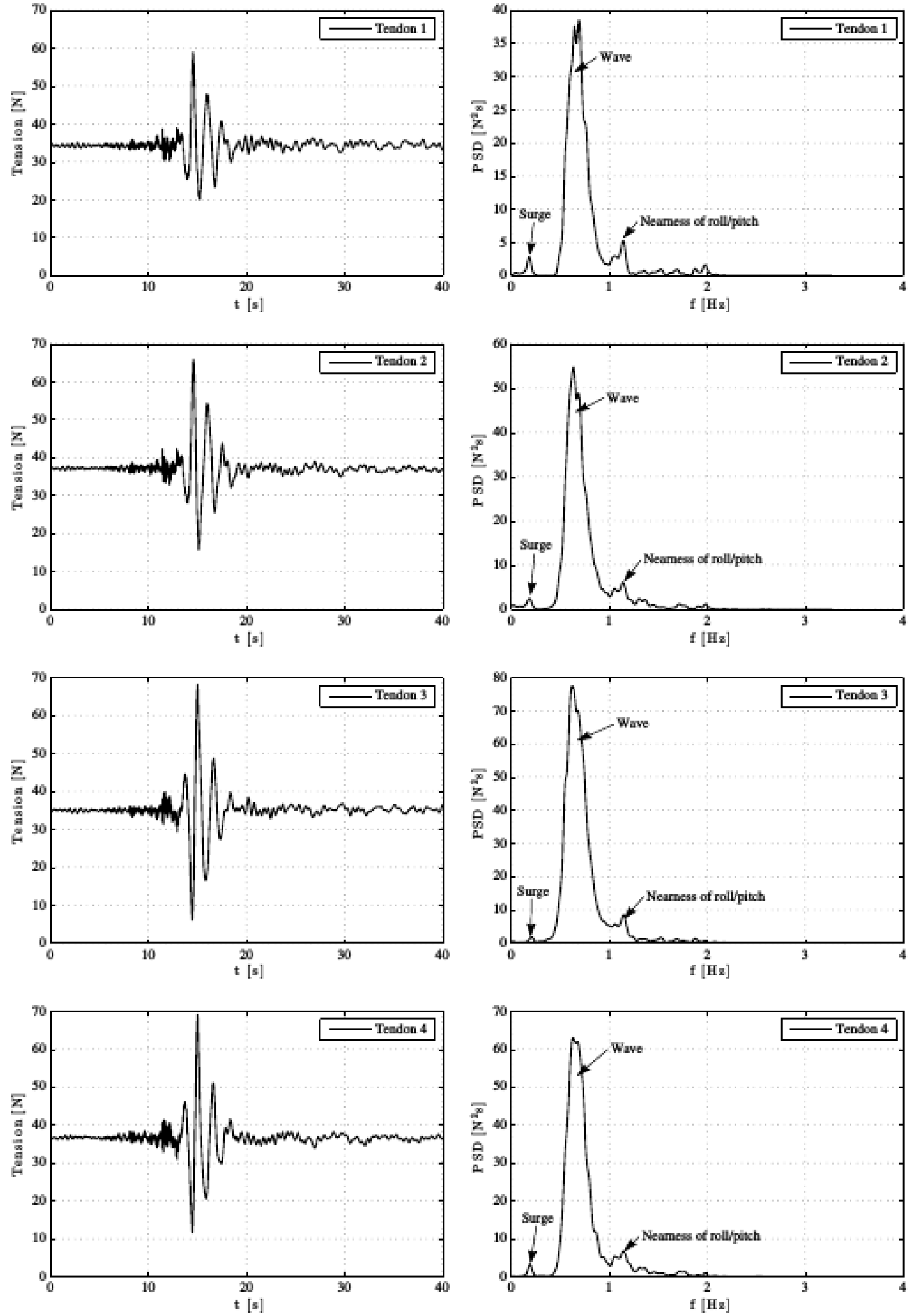


Figure 7.38: Tendon tensions of structure 1 when subjected to focused wave number 8 without wind (S1F08).

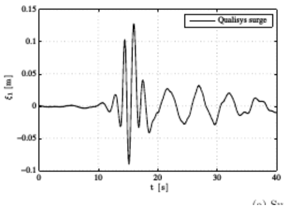
Conclusions

Scaling principles

Froude-scaling of water
and global aerodynamic loads

Low Re leads to re-designed rotor
with larger chord

Preliminary results
Extreme environment



Focused waves

Response in
platform motion

Spectral analysis

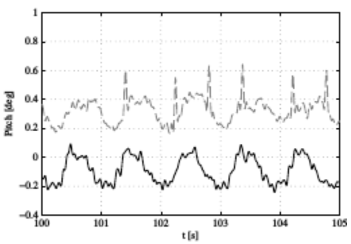
Aerodynamic design

10 MW rotor scaled to 1:60.
Collective pitch and rpm control

2D wind tunnel test at Re down
to 30k incorporated in design

Wind generator 4x4 meter
max speed of 1.7 m/s

Preliminary results
Gentle environment

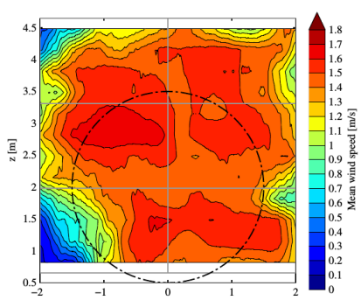


(e) Pitch - Seastate 5

Wind effects and rotor
effects clearly detectable

Damping effects and RAOs
investigated

Setup and validation



(a) Mean wind speed.

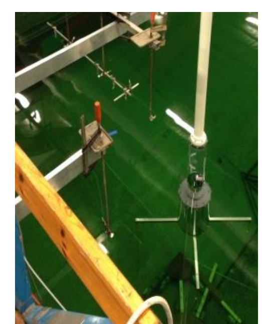
Wind field measured in
sweeps at 12 levels.
TI ~ 6 %

Fairly uniform with slight
'under cut'

Floater design

TLP Ø18m,
height 25m,
draft 37m

Static and
dynamic design
considerations



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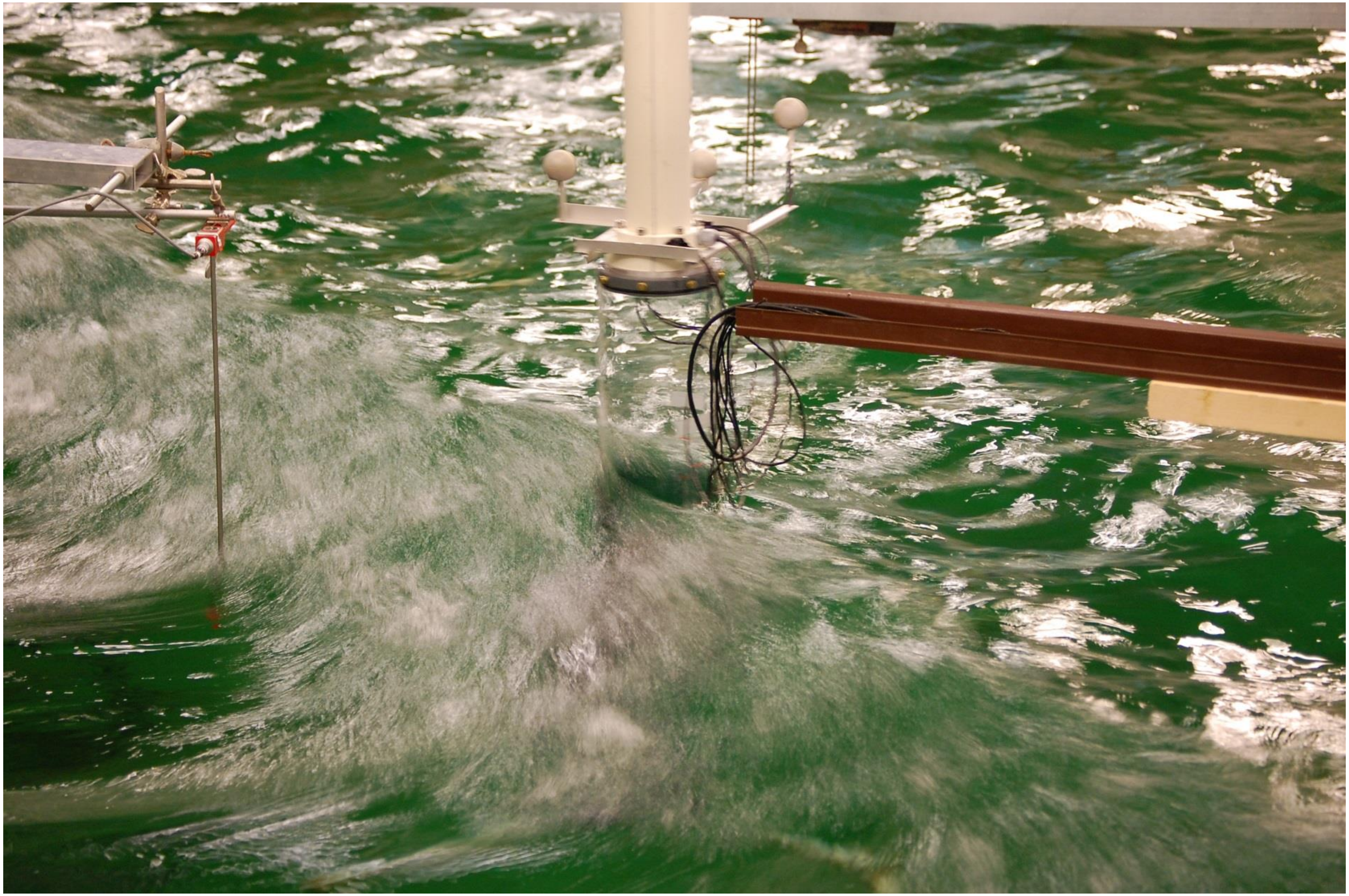

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