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

Bredmose, Henrik; Mikkelsen, Robert; Hansen, Anders Mandrup; Laugesen, Robert; Heilskov, Nicolai; Jensen, Bjarne; Kirkegaard, Jens

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Henrik Bremose, Robert Mikkelsen, Anders Mandrup Hansen, Robert Laugesen
DTU Wind Energy
hbre@dtu.dk

Nicolai Heilskov, Bjarne Jensen, Jens Kirkegaard
DHI

Part of the INNWIND.EU project

DTU Wind Energy
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Preliminary results
Extreme environment

Preliminary results
Gentle environment

Scaling principles

Aerodynamic design

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

\[ \frac{M_p}{\rho_{wp} Vol_p} = \frac{M_m}{\rho_{wm} Vol_m} \quad \Rightarrow \quad \frac{M_p}{M_m} = \frac{\rho_{wp}}{\rho_{wm}} \lambda^3 \]

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

Froude scaling of hydrodynamics:

\[
\lambda = \frac{L_p}{L_m} \\
\frac{T_p}{T_m} = \sqrt{\lambda} \\
\frac{M_p}{M_m} = \frac{\rho_w}{\rho_{wm}} \lambda^3
\]

Keep overall geometry

Keep consistent scaling of rotational frequency

Preserve tip speed ratio

Thrust force and thrust coefficient

\[
R_{rotor,m} = R_{rotor,p}/\lambda \\
\omega_m = \omega_p/\sqrt{\lambda} \\
\frac{\text{TSR}_p}{\text{TSR}_m} = \frac{\omega_p R_p}{u_{am}} \frac{u_{am}}{\omega_m R_m} = 1 \\
\Rightarrow u_{a,m} = u_{a,p}/\sqrt{\lambda}
\]

\[
F_T = \rho_a C_T A u_a^2 \sim \rho_w \lambda^3 \\
\Rightarrow \frac{C_{Tp}}{C_{Tm}} = \frac{\rho_{wp}}{\rho_{wm}}
\]
Air velocities (model scale) $\sim 1.5$ m/s

Re (proto scale) $\sim 10M$

Re (model scale): $\sim 25k$
Scaling principles

Air velocities
(model scale) ~ 1.5 m/s

Re (proto scale) ~ 10M

Re (model scale): ~ 25k

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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
Scaling principles

- Air velocities (model scale) $\sim 1.5$ m/s
- Re (proto scale) $\sim 10M$
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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

![Graph showing environmental conditions with a range of values for Tp and Hs with corresponding U value.]

Johannesen et al (2002); Bachynski (2014)

Design requirements

- max tendon angle with vertical: 10 deg
- max tension: $1.8 \times T_0$
- min tension: $0.2 \times T_0$
The floater
Preliminary results
Extreme environment

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(model scale) \(\sim 1.5\) m/s
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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 101 - 104

(b) Sea states 105 - 108

(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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Aerodynamic design

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Preliminary results

Regular, gentle waves
Preliminary results

Irregular waves close to rated wind speed with and without wind
Preliminary results

Irregular waves at close to rated wind speed

Figure 7.26: Tower acceleration - Seastate 5 - Wind
Preliminary results
Extreme environment

Scaling principles
Air velocities
(model scale) ~ 1.5 m/s
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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

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

Floater design
- TLP Ø18m, height 25m, draft 37m
- Static and dynamic design considerations

Preliminary results
- Gentle environment
  - Wind effects and rotor effects clearly detectable
  - Damping effects and RAOs investigated
- Extreme environment
  - Focused waves
  - Response in platform motion
  - Spectral analysis

Setup and validation
- Wind field measured in sweeps at 12 levels. TI ~ 6 %
- Fairly uniform with slight 'under cut'
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