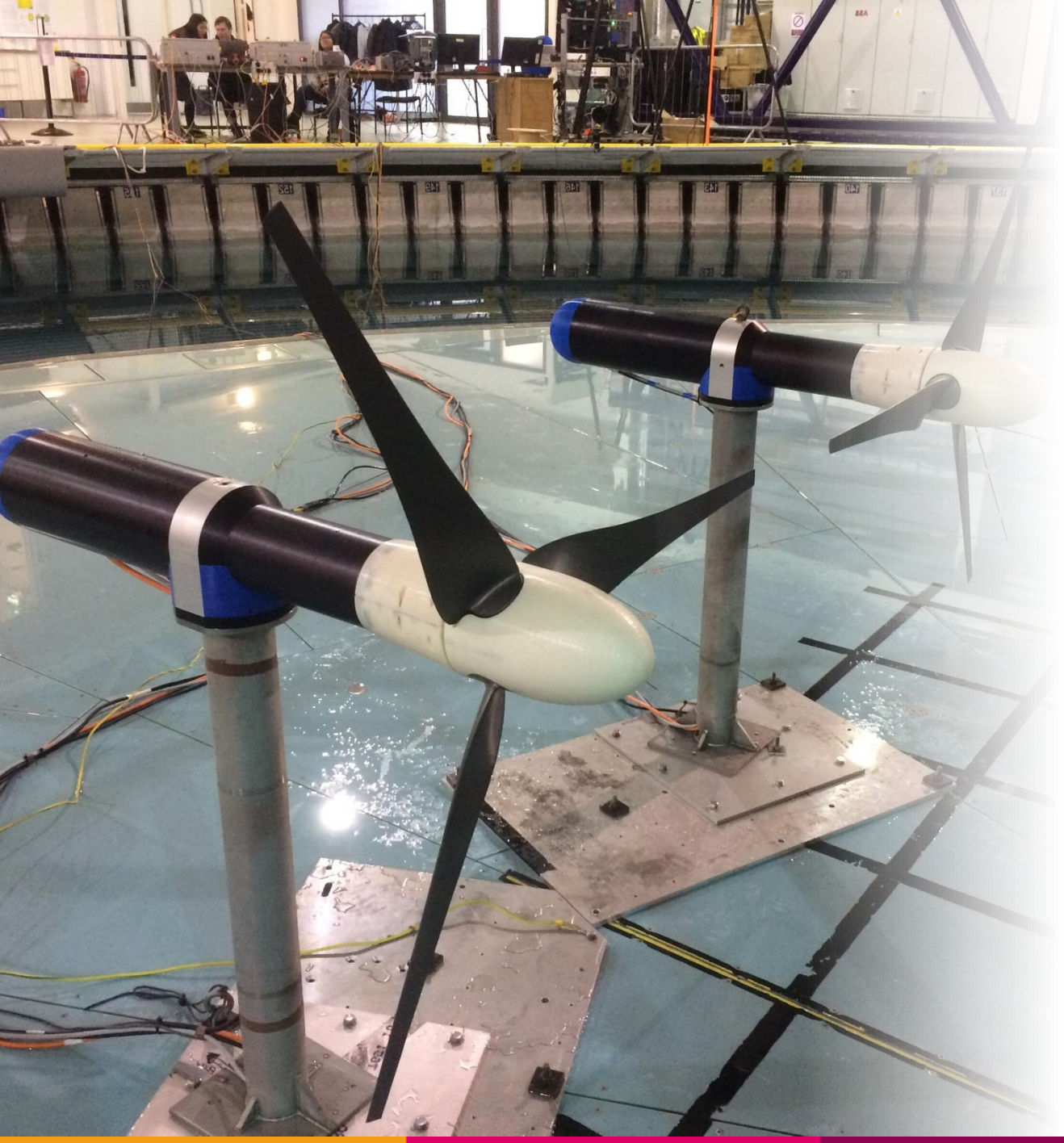


DEPARTMENT OF ENGINEERING SCIENCE

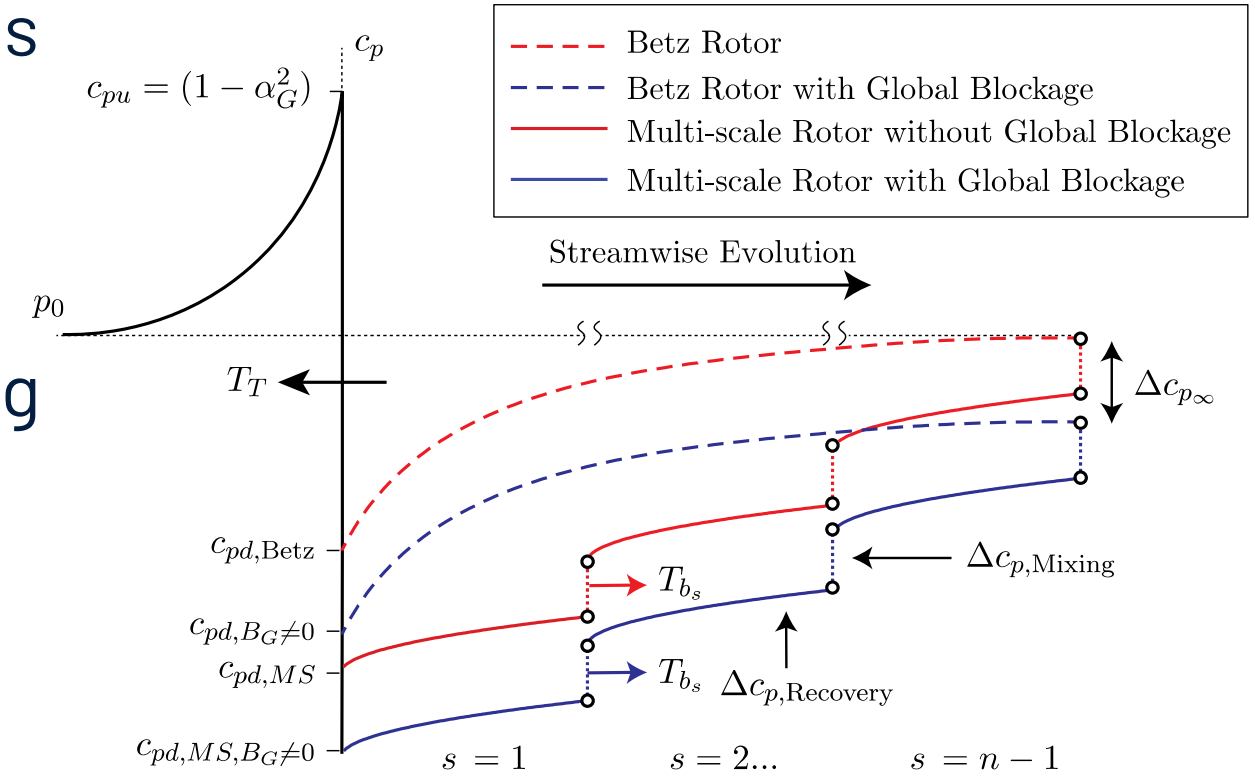
UNIVERSITY OF OXFORD

Modelling loads on closely-spaced rotors

Christopher Vogel

Modelling blockage effects

- Betz limit only applies for some cases
- Flow confinement allows a pressure drop to develop, enabling greater thrust and power on rotor
- Wake mixing is important for allowing pressure recovery in the wake
- Multi-scale mixing can allow greater pressure drops to be sustained, and thus greater power
- A lot of energy can be dissipated in the wake – trade-off between energy extraction efficiency and resource utilisation efficiency

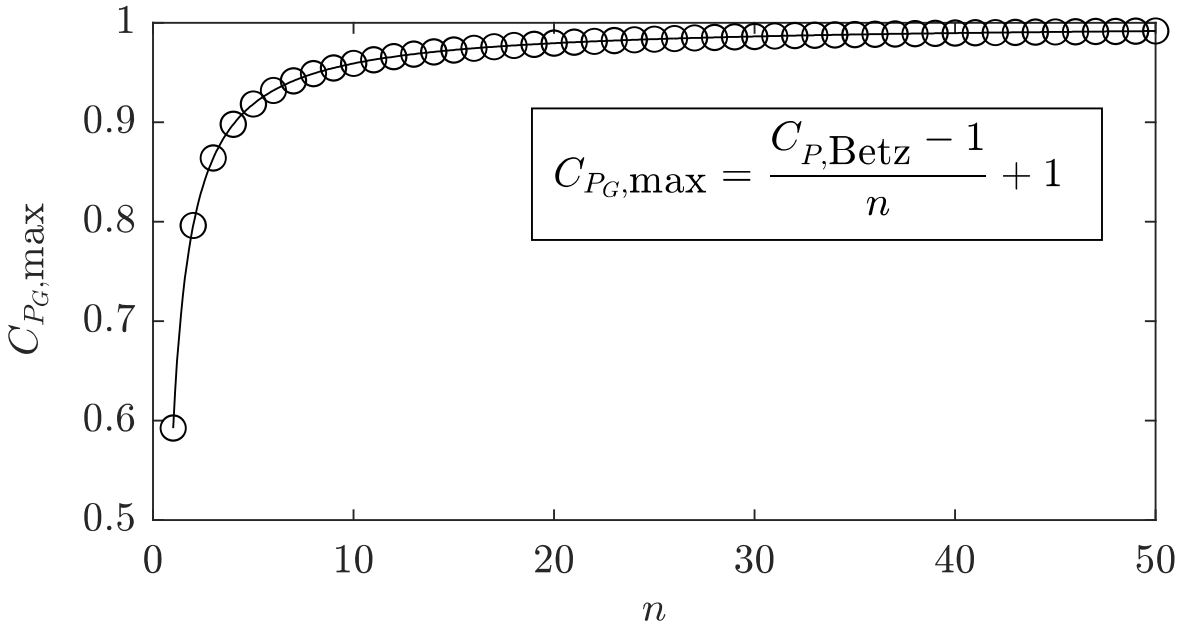


Dehtyriov et al. (2021) *J. Fluid Mech.* 927: A40

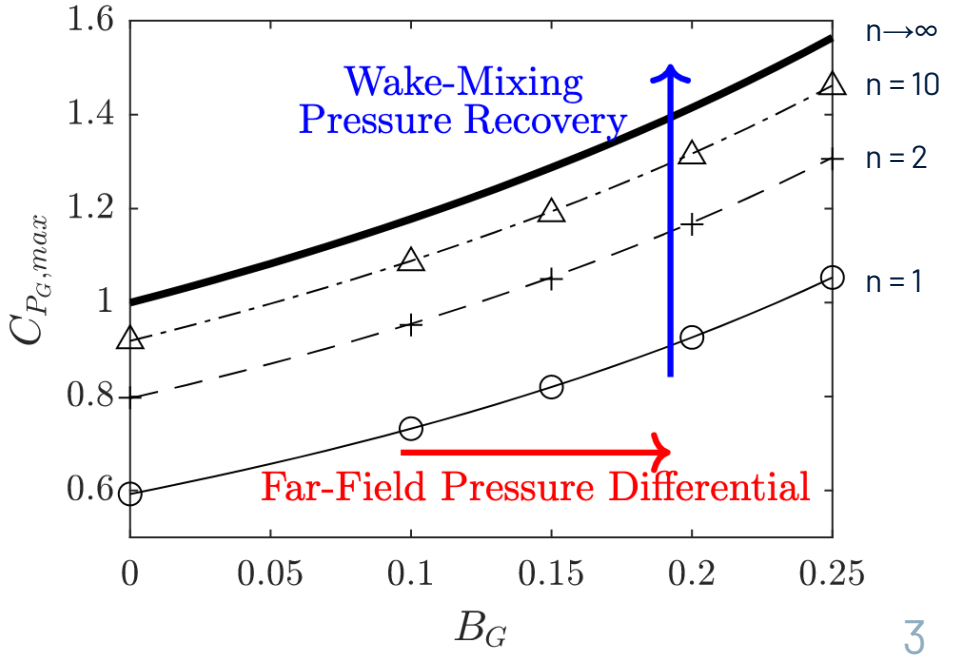
Multi-scale modelling

- Multi-scale models developed to account for differences in local and global confinement
- Max C_P tends to unity for many scales of mixing, *even when the outermost scale is unblocked*
- Max C_P is higher when the outermost scale is blocked

Can theoretical performance improvements be achieved by real turbines?

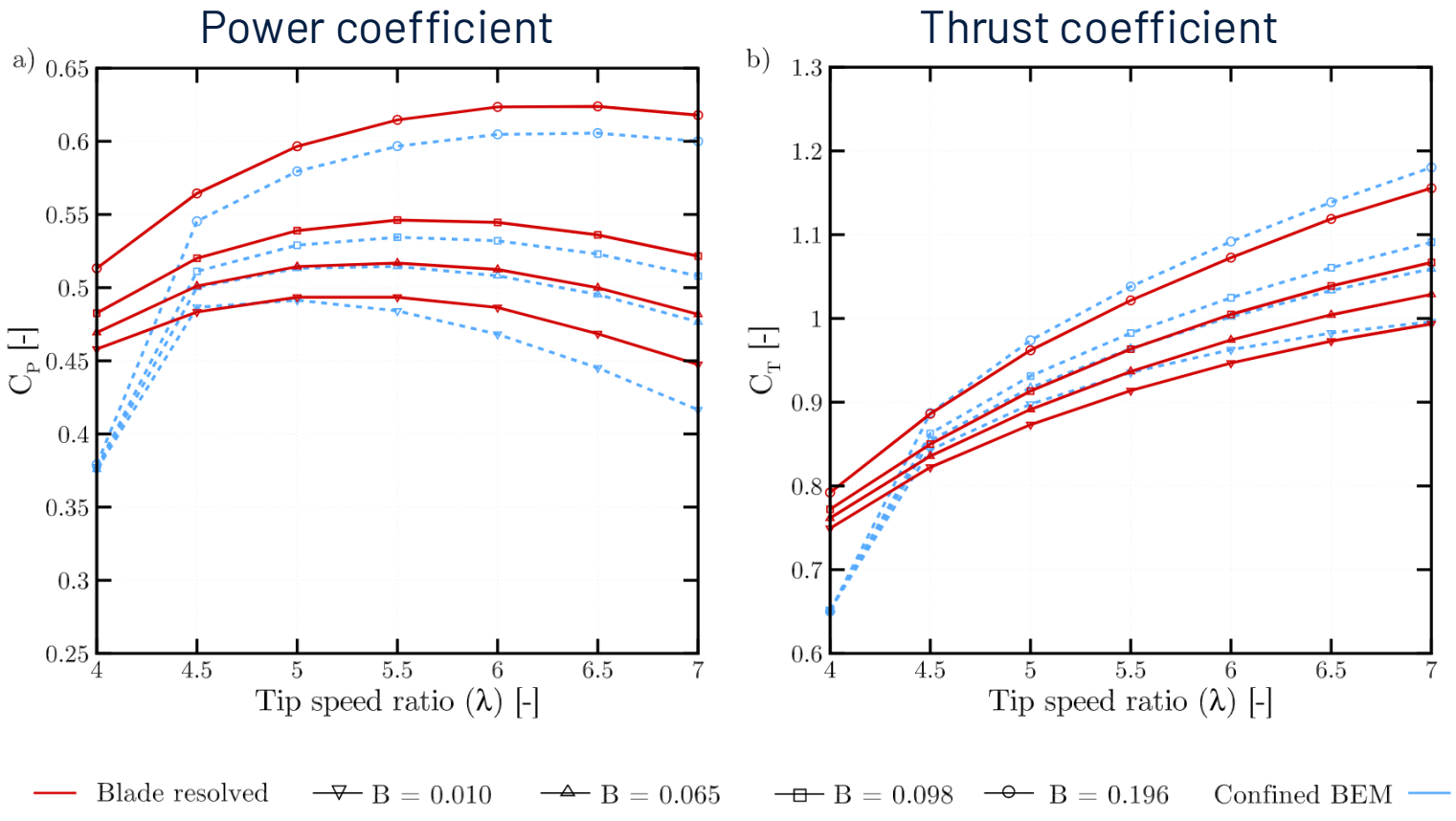


Dehtyriov et al. (2021) *J. Fluid Mech.* 927: A40



BEM + Blockage

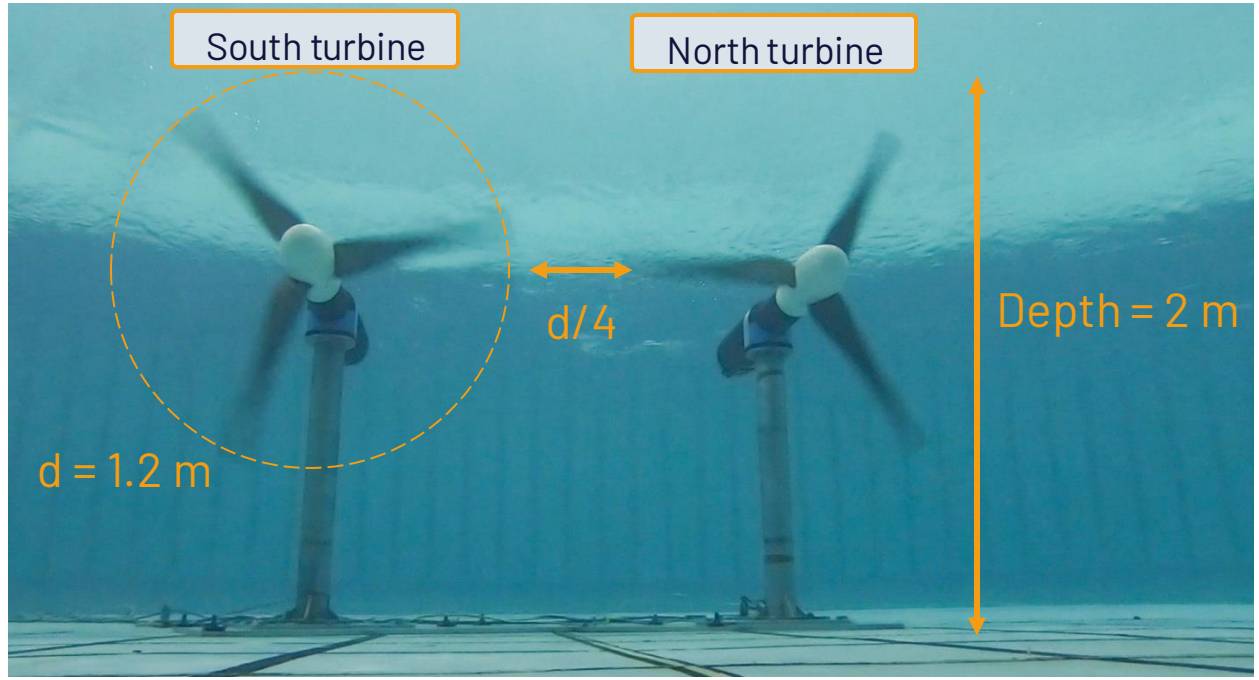
- Inviscid blockage effects can be incorporated into rotor models e.g. BEM
- Momentum equations are modified to account for blockage
- Generally good agreement with blade-resolved simulations
- Limitations:
  - Sensitive to input lift and drag polars
  - Possible issues with high-thrust correction models

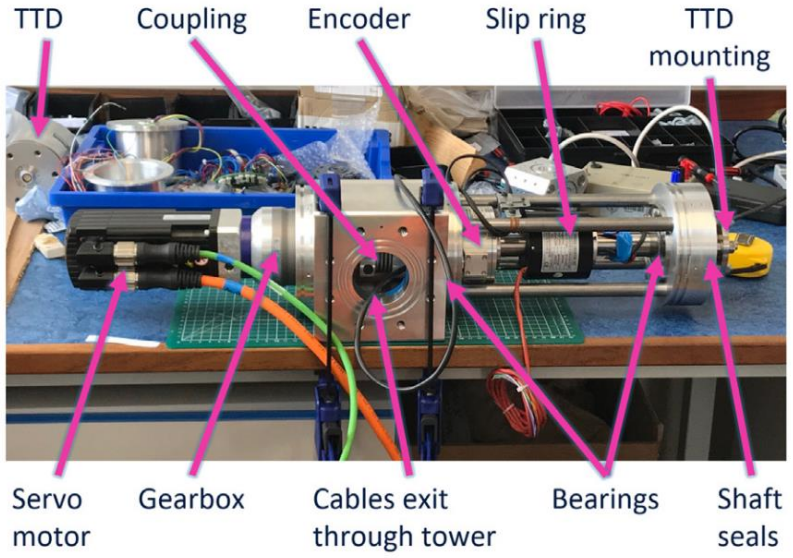


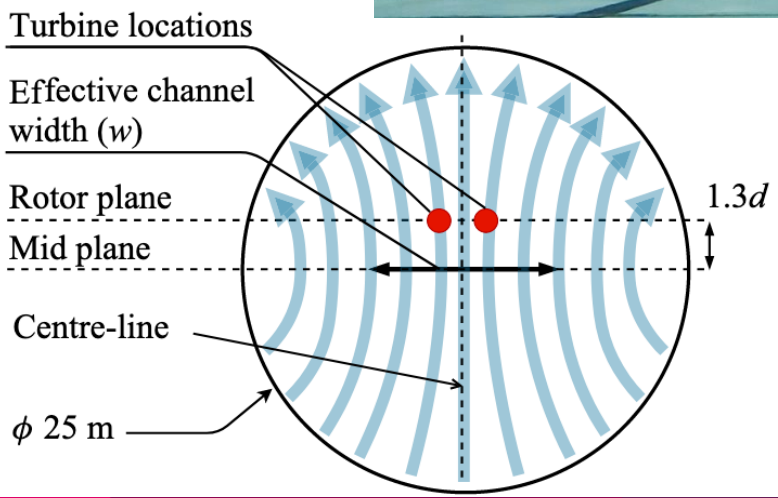
Vogel et al. (2018) *Ocean Engineering* 169: 215-226

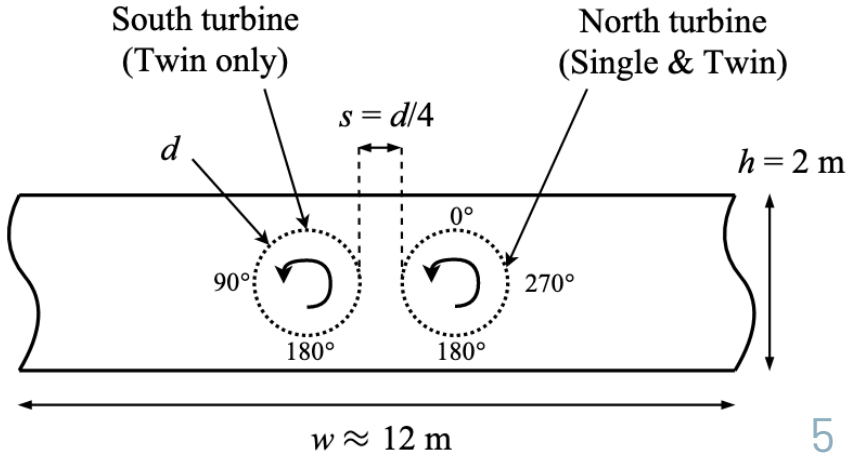
Rotor-rotor interactions

- Side-by-side testing of a single and two 1.2 m diameter turbines at FloWave, University of Edinburgh
- Co-rotating turbines designed for tip-to-tip spacing s/d = 0.25









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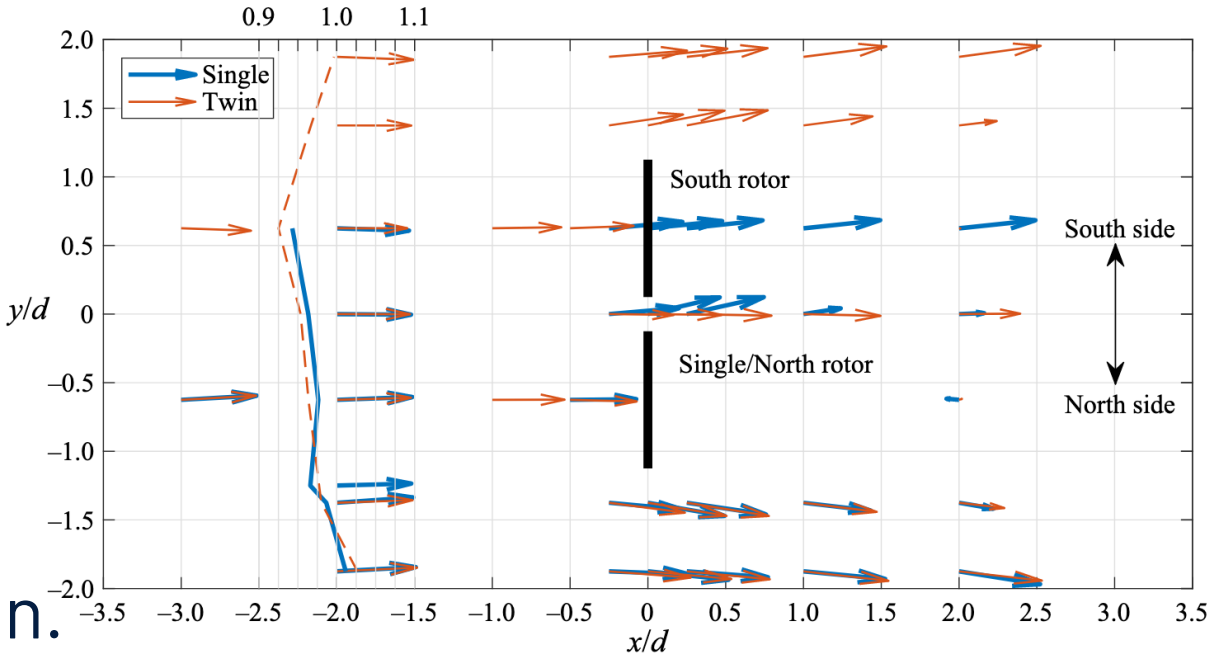
Rotor-rotor interactions

Flow

Single: flow deceleration in wake, acceleration around rotor.

Twin: acceleration observed between rotors and stronger bypass acceleration.



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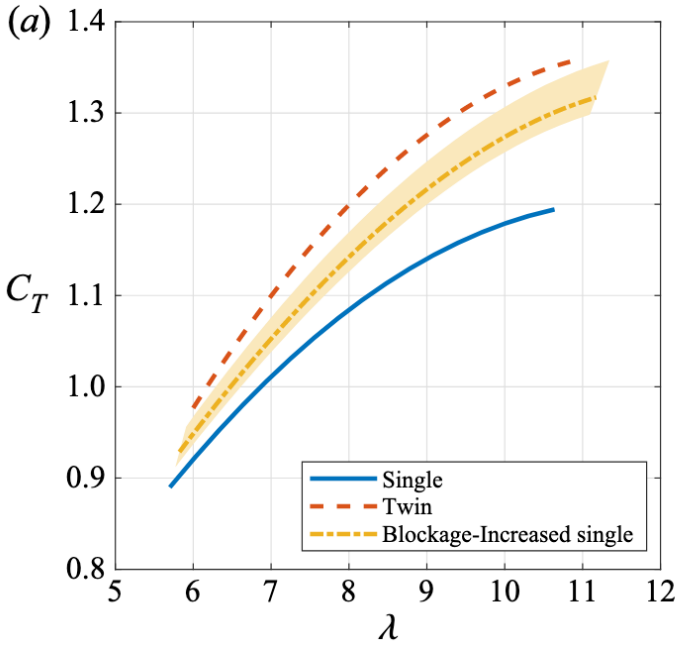
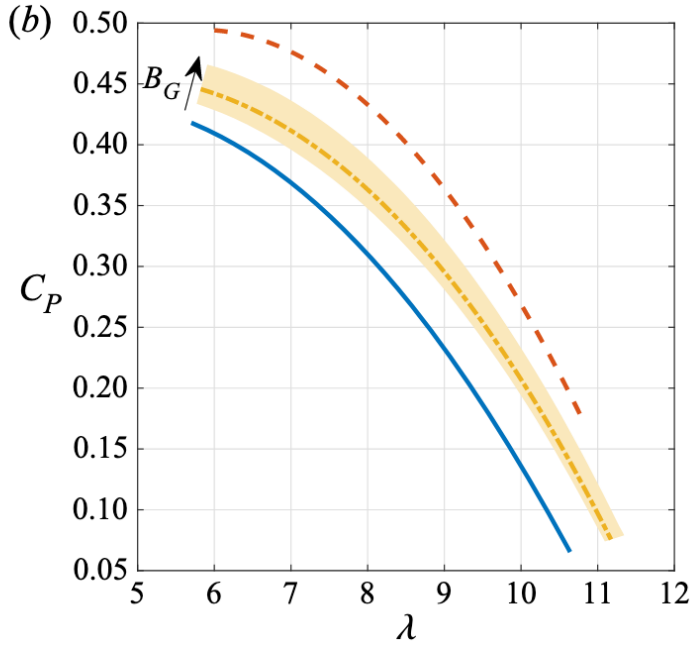
Thrust coefficient



Power coefficient



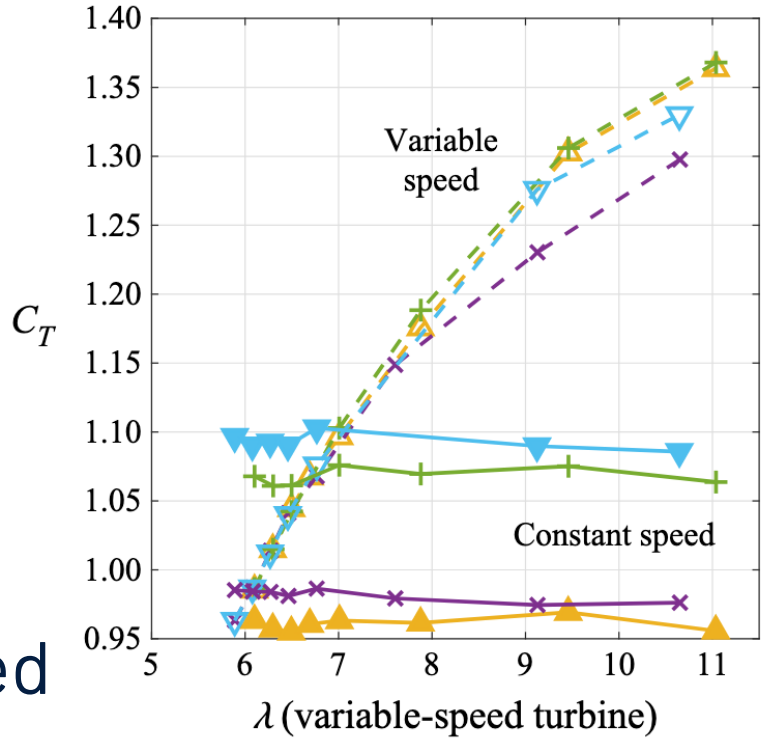
Performance

Increase in power and thrust from **single** to **twin** configurations is larger than expected from **blockage alone** – a beneficial rotor interaction occurs.

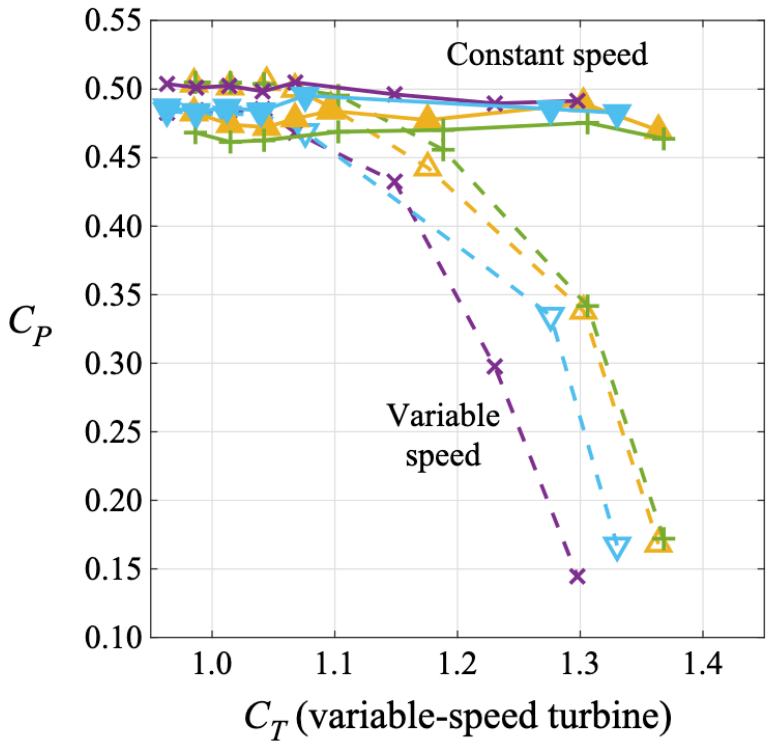
Interactions depend on turbine speed

- Interactions between rotors depend on both proximity and also how the rotors are operating
- Impact on turbine is observed due to changing operation of neighbour, even when the turbine operates at constant speed

Thrust coefficient



Power coefficient



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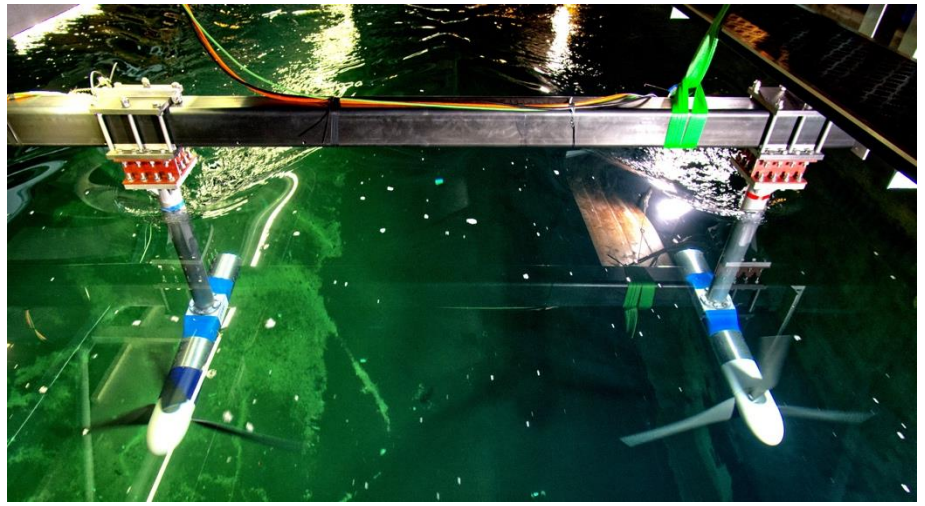
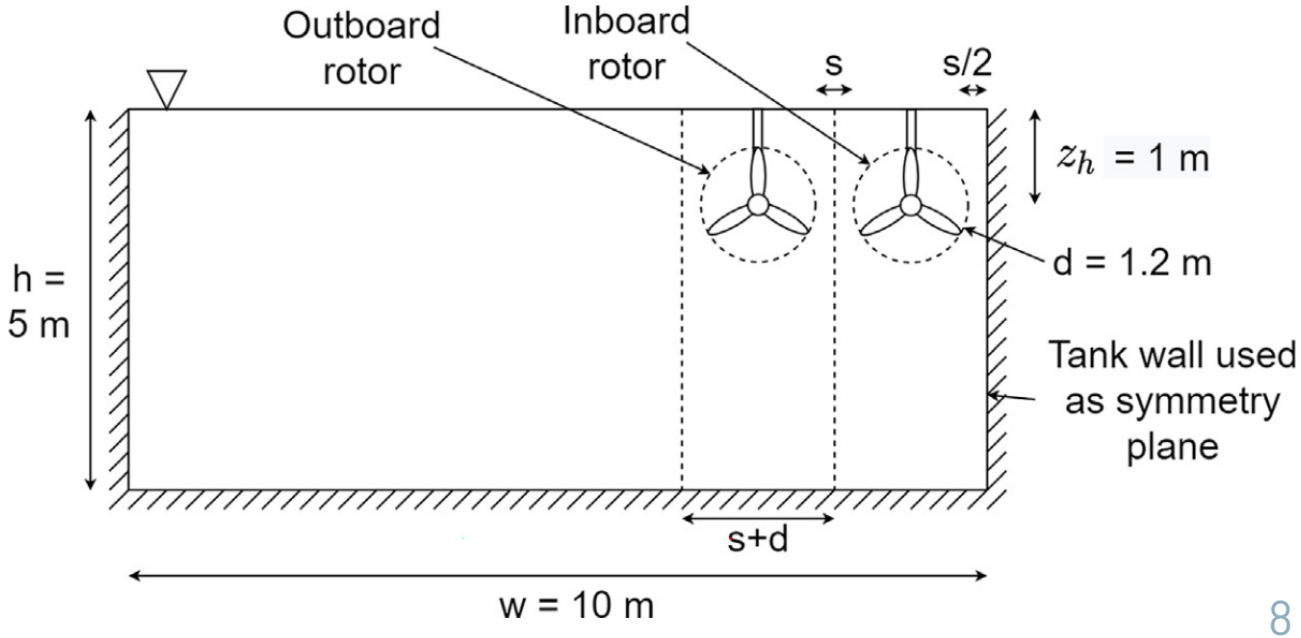
Overall observation:

Exploiting rotor-rotor interactions led to ~20% increase in peak power with corresponding ~10% increase in thrust

Impact of rotor spacing

- Towing tank experiments performed at SSPA, Gothenburg
- Turbines mounted from above on a beam to allow spacing to vary
- Tank sidewall used as a symmetry plane
- Measurements:
  - Whole-rotor thrust and power
  - Blade root bending moments (flapwise and edgewise)
- Reynolds-independence above tow speeds about 0.8 m s^{-1}





McNaughton et al. (2023) *J. Fluids Struct.* 118: 103844

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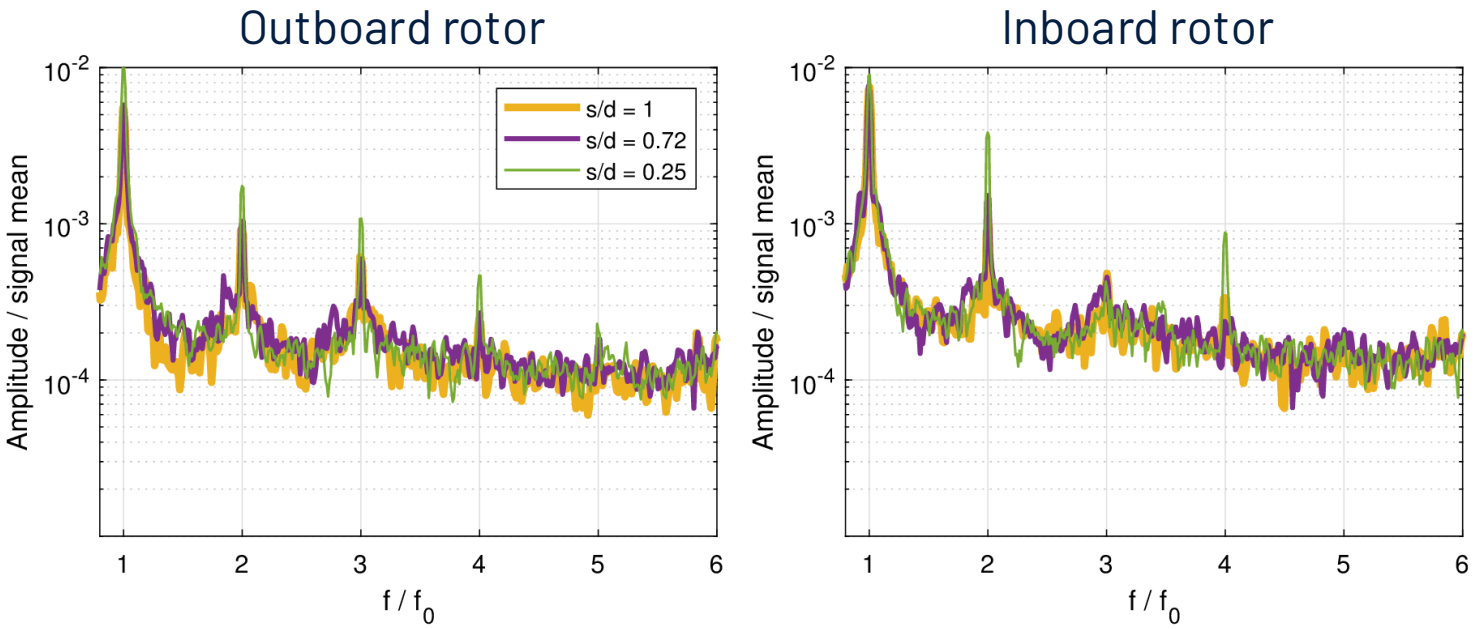
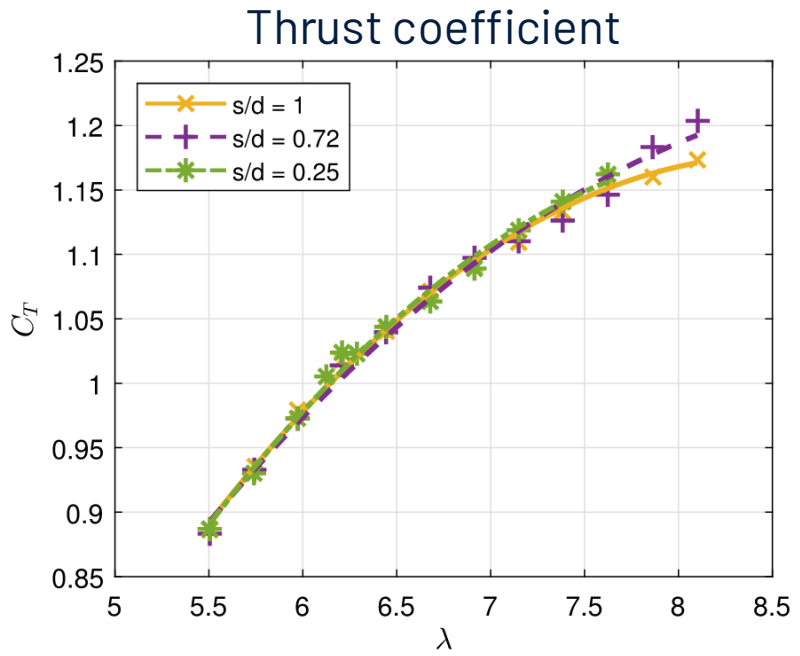
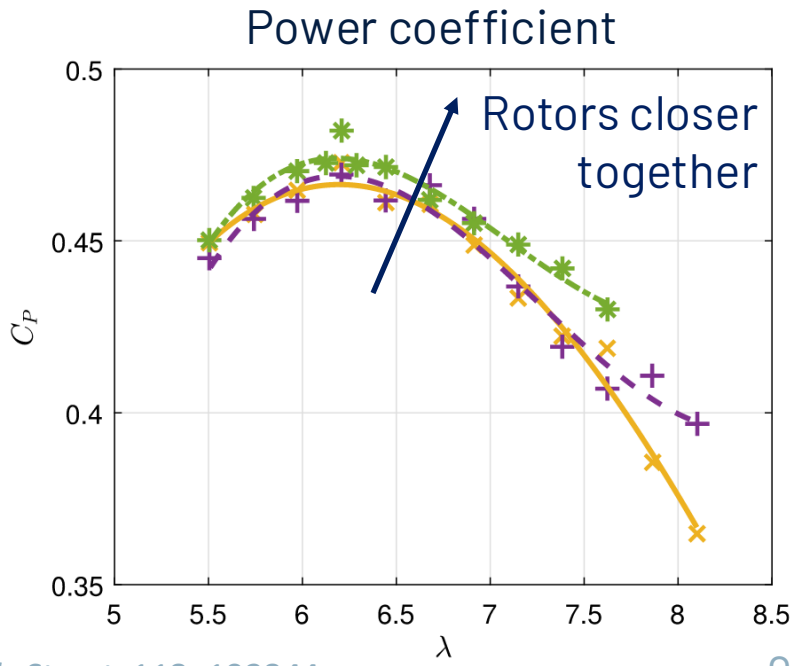
Impact of rotor spacing

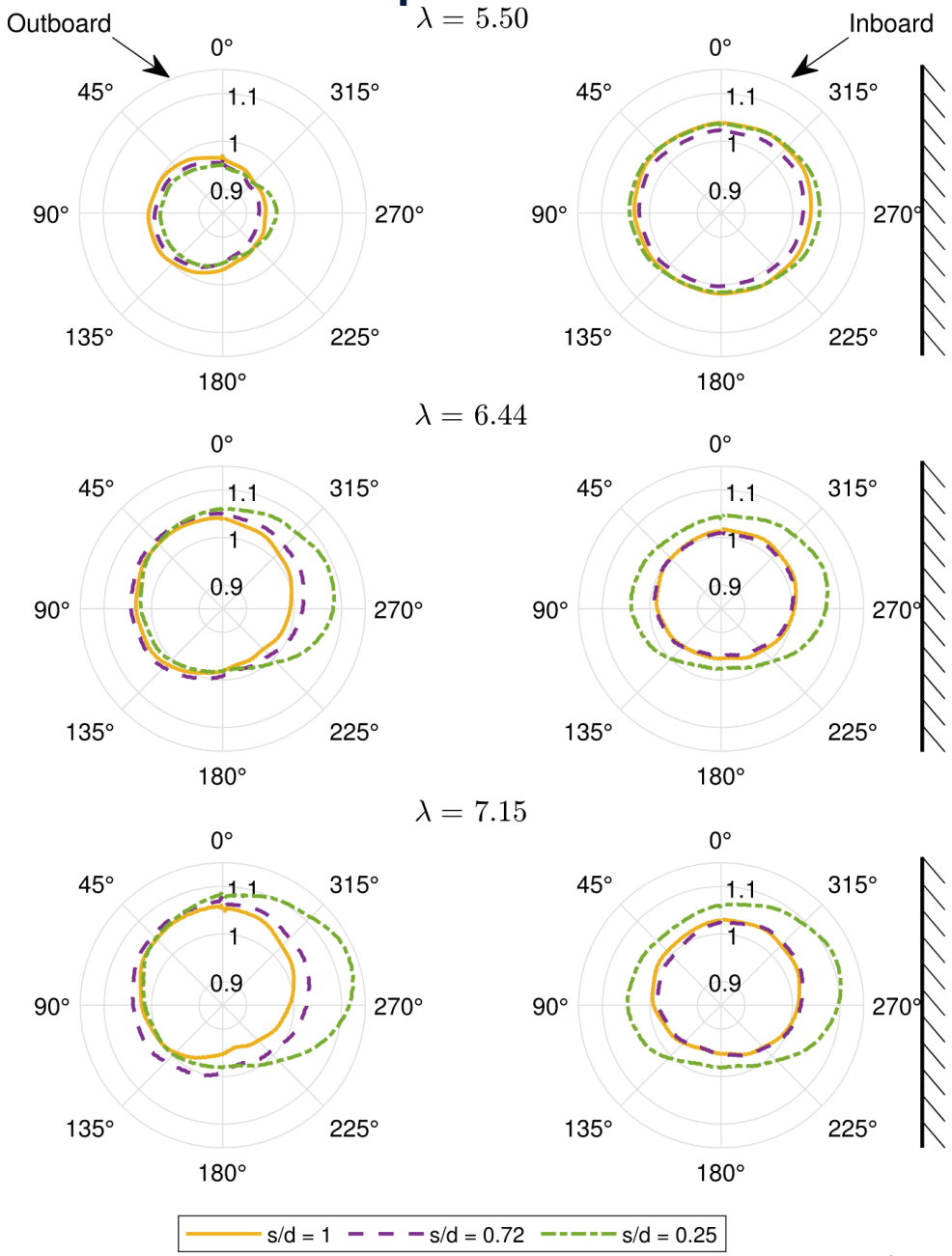
- Decreasing tip-to-tip spacing increased peak power coefficient, little change observed for C_T
- Power of 2*p* frequency fluctuation in flapwise root bending moment increases as turbine spacing decreases – stronger interactions



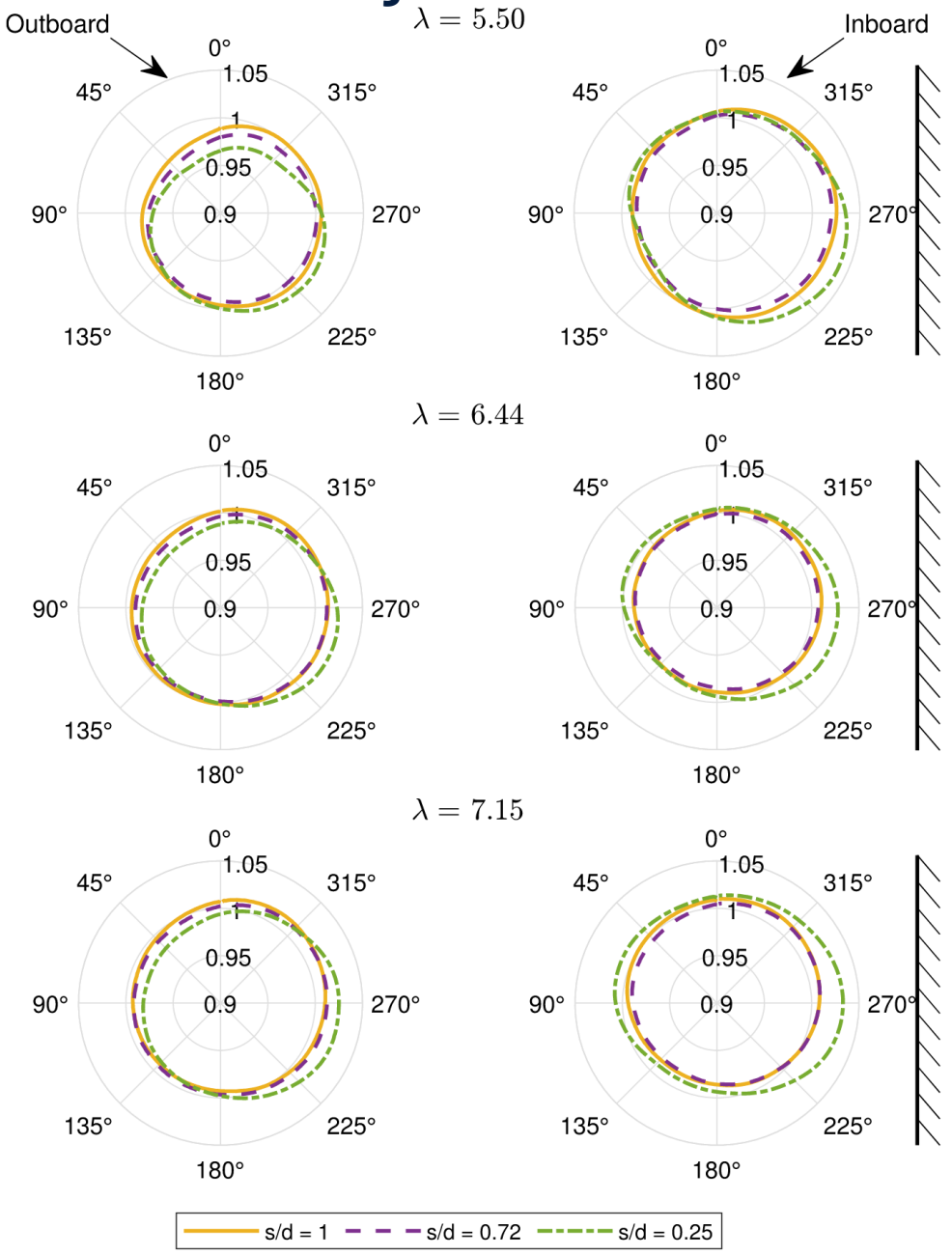




Flapwise RBM

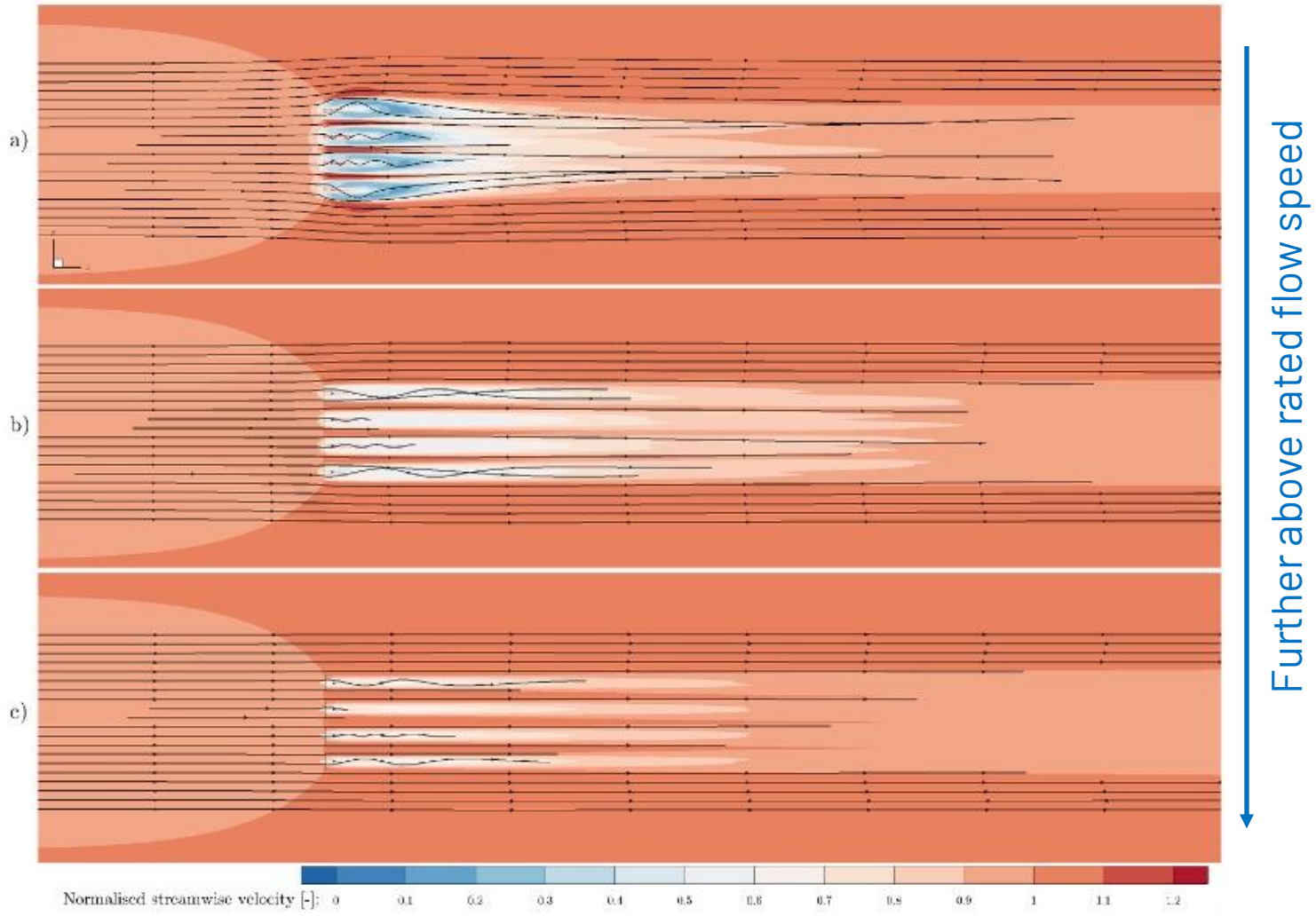


Edgewise RBM



Rotor interactions depend on thrust

- Blockage defined as a geometric ratio, but interaction strength depends on thrust
- Above rated flow speed inter-turbine interactions can become small
- Support structures (not simulated here) may have an important influence on interactions



Vogel & Willden (2018) *Int. Marine Energy* 1(1) : 61-70

Conclusions

Modelling

- Far-field pressure changes drive the improved performance available to multi-scale and multi-rotor systems
- Specific corrections for BEM & actuator-based modelling of closely-spaced rotors are likely required

Loads

- Proximity to neighbouring rotors can increase power and thrust
- Interactional effects are thrust-dependent
- Close spacing of rotors enhances $2p$ load frequencies – potentially important for fatigue calculations

Thank you for your attention

christopher.vogel@eng.ox.ac.uk