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Very Large Wind Farm Design Improvement Using Multi-Fidelity Modelling Approaches

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An extended theoretical model, which is based on a generalised two-scale coupled momentum conservation argument, is proposed to estimate aerodynamic effects of support structures on the performance of ideal very large wind farms. The model suggests that the parameter $(A_s/A)\cdot C_D^*$, which represents an effective support-structure drag, plays an important role in the design and optimisation of very large wind farms. To validate this extended model, Detached-Eddy-Simulations (original version with Spalart-Allmaras model) of a periodic staggered array of actuator discs with and without support structures are conducted.

Theoretical model

Based on original model (Nishino 2016)

$$\langle\tau_w\rangle S + T + D = \frac{\Delta p}{\Delta p_0}\tau_{w0}S$$

$$T = \frac{1}{2}\rho U_F^2 A\cdot C_T^*$$

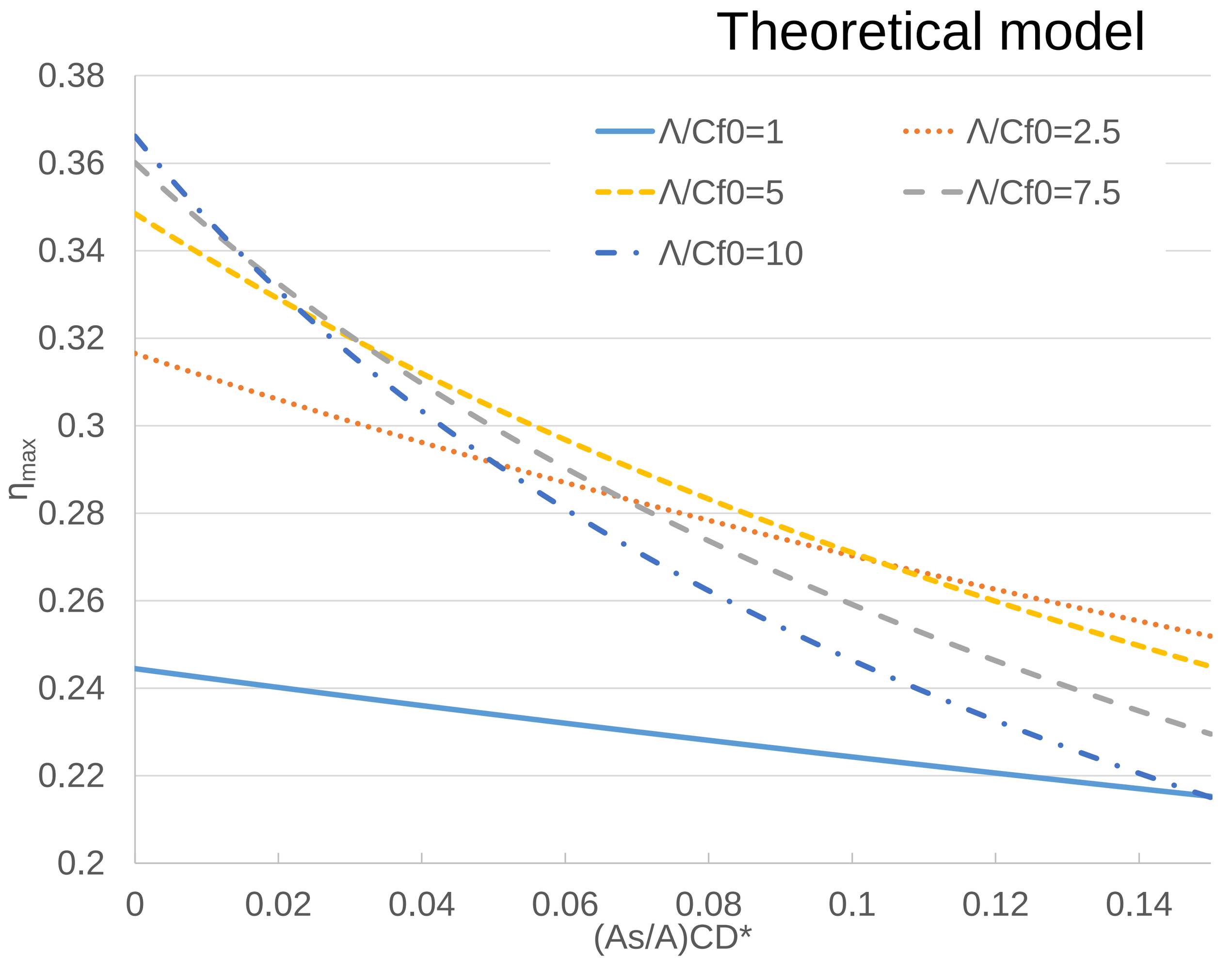
$$D = \frac{1}{2}\rho U_F^2 A_s\cdot C_D^*$$

Generalised two-scale coupled momentum equation

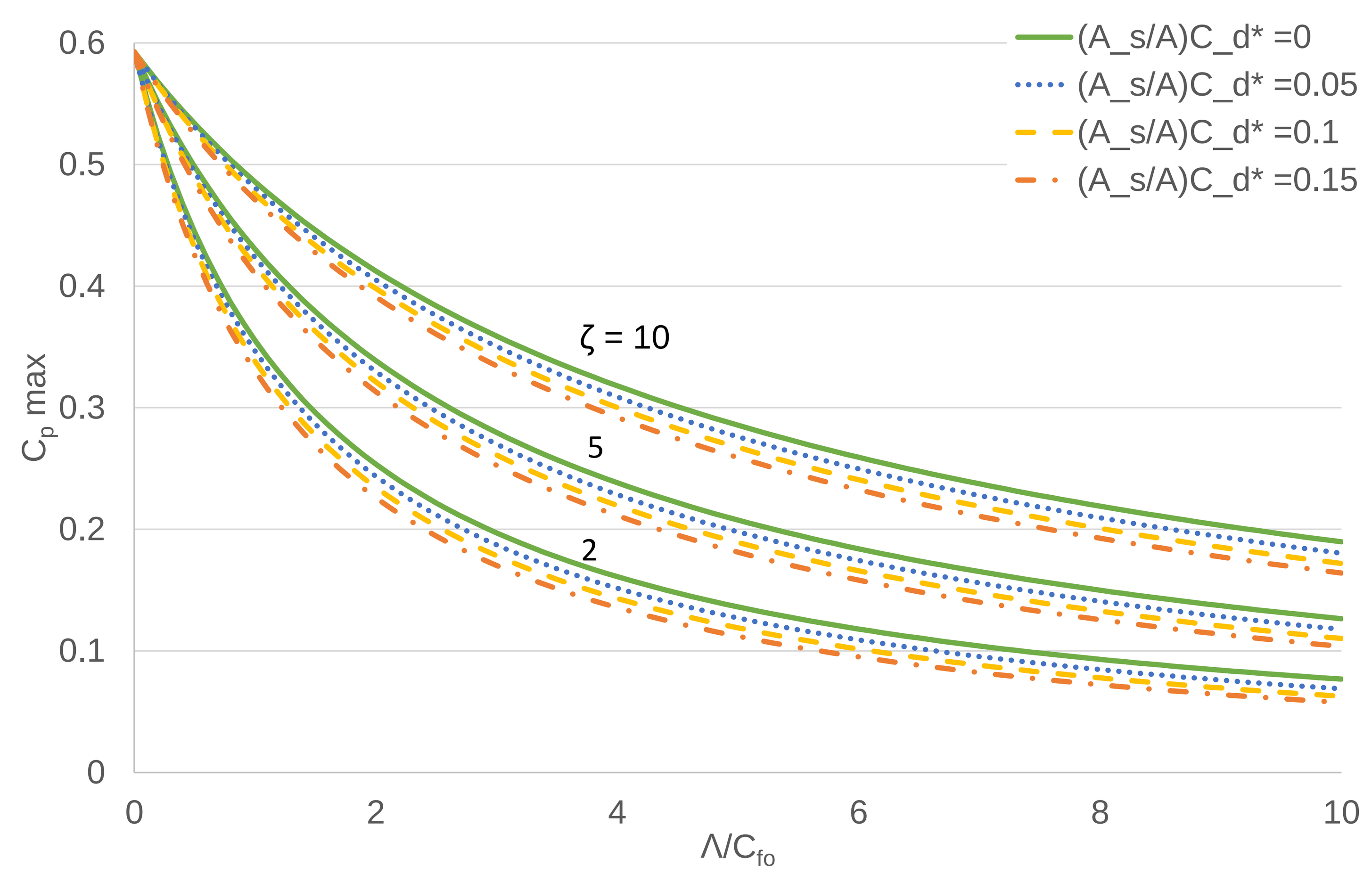
$$\frac{\Lambda}{C_{f0}}\cdot\beta^2\cdot\left(4\alpha(1-\alpha)+\frac{A_s}{A}C_D^*\right)-1+\beta^\gamma = \zeta(1-\beta)$$

Normalised power density

$$\eta = \frac{\text{Power}}{\tau_{w0}U_{F0}S} = \frac{\frac{1}{2}\rho U_{F0}^3 A\cdot C_P}{\tau_{w0}U_{F0}S} = \Lambda\cdot\frac{1}{C_{f0}}\cdot C_P = \Lambda\cdot\frac{1}{C_{f0}}\cdot 4\alpha^2(1-\alpha)\beta^3$$



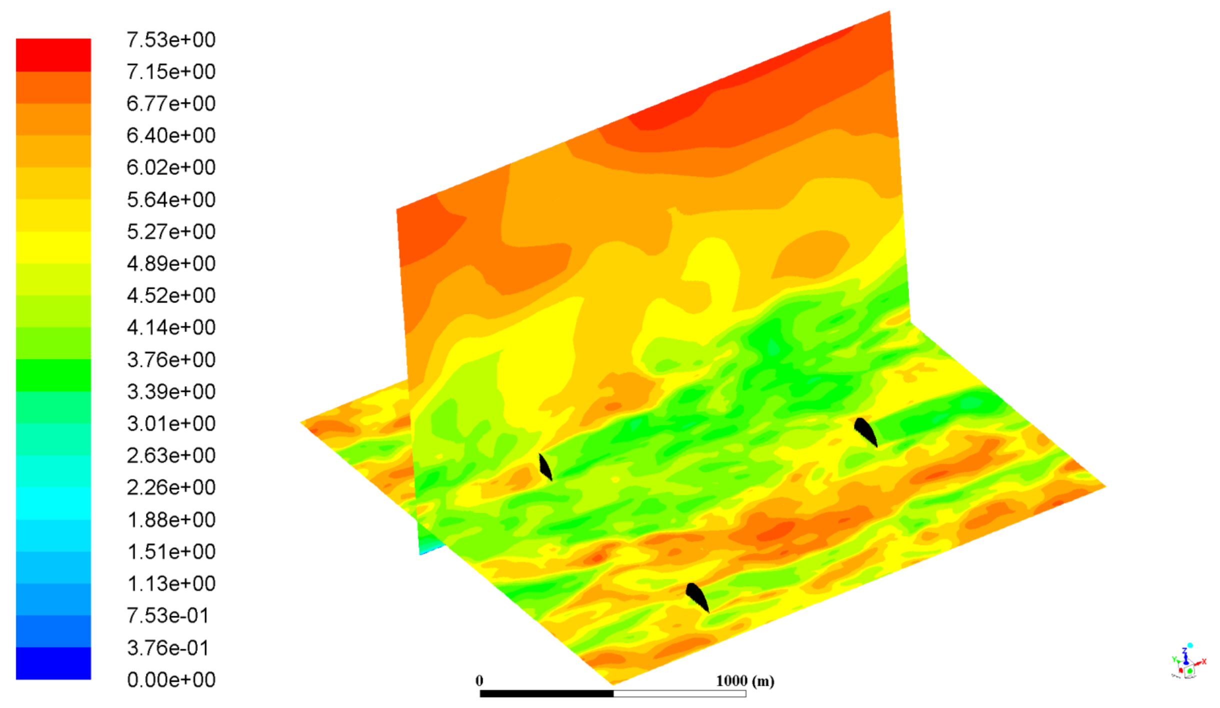
The maximum normalised power density η_{max} against the normalised support-structure drag $(A_s/A)C_D^*$ for various effective farm density Λ/C_{f0} (ζ =0 for all these results).



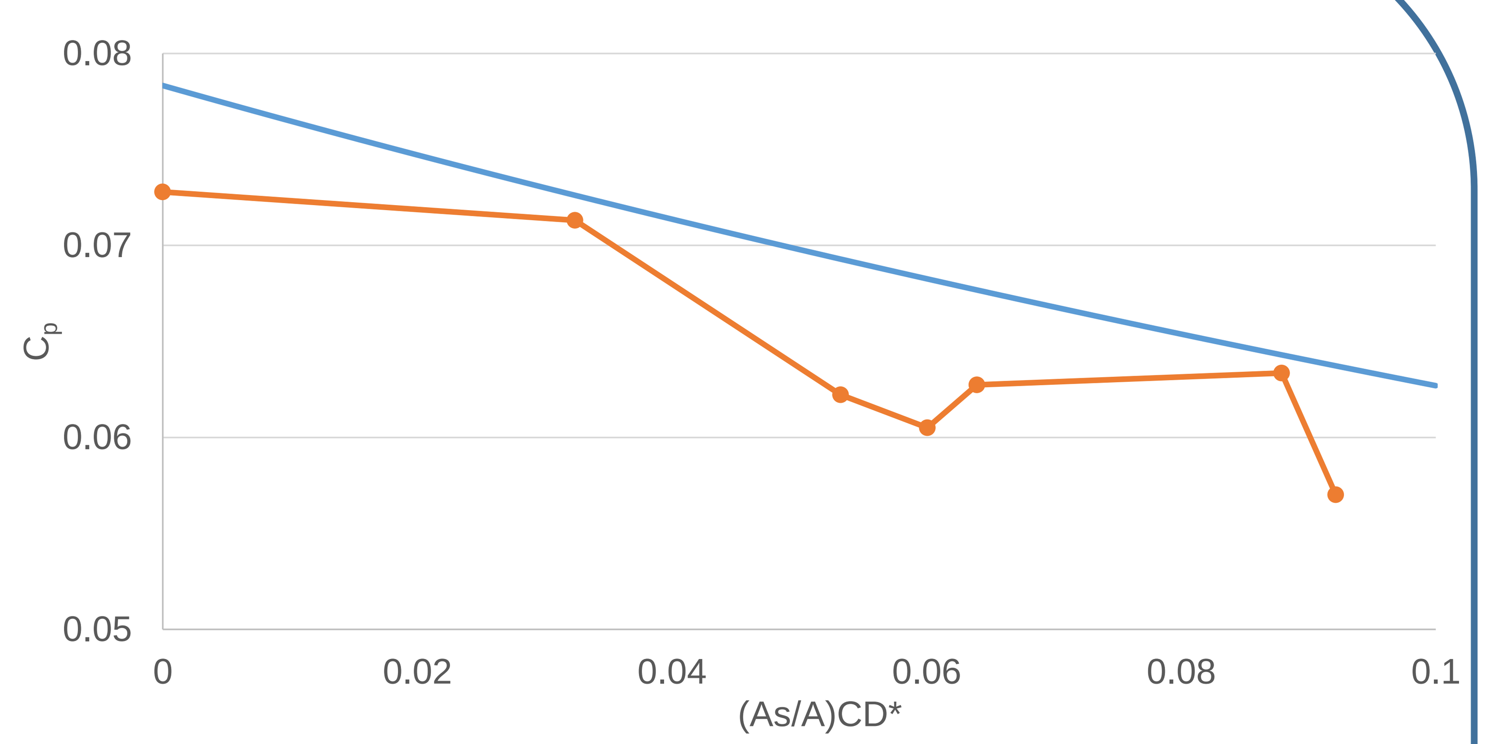
The maximum power coefficient C_p max against the effective farm density Λ/C_{f0} for various normalised support-structure drag $(A_s/A)C_D^*$ and ζ.

CFD results

- Wall-Modelled Large Eddy Simulations (DES with Spalart-Allmaras model)
- Constant streamwise pressure gradient for all cases
- Constant ground roughness length (z_0 = 0.05m)
- Periodic conditions applied to stream and spanwise directions
- Momentum sink method applied to the rotor (K = 0.5, no rotation) and support structure (K_s)



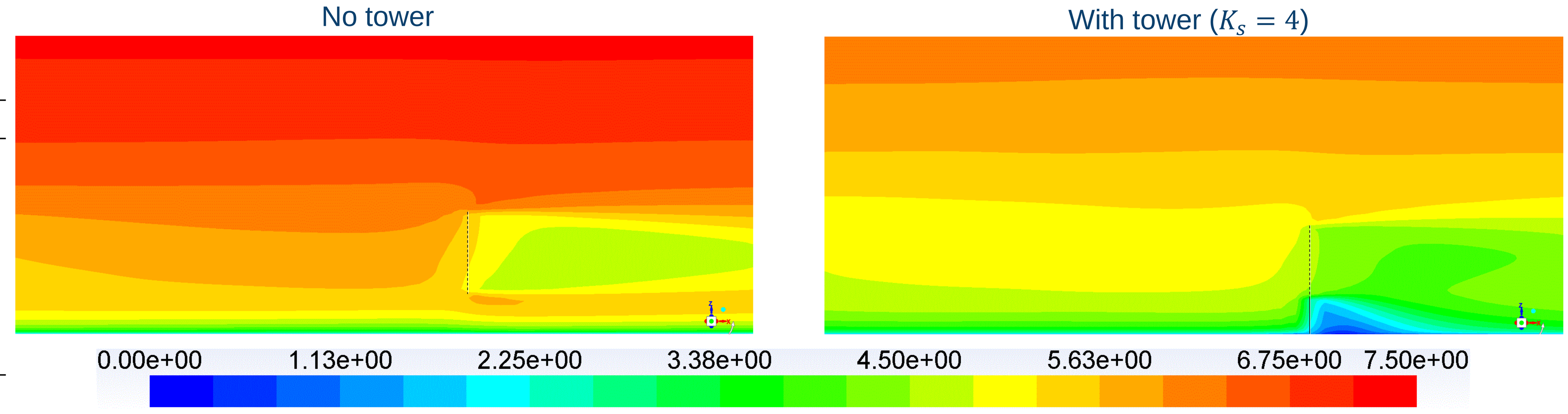
Instantaneous streamwise velocity [m/s] contours ($K_s = 4$) on a vertical (centre of a turbine) and horizontal plan (hub height)



Comparison of C_p between CFD (orange) and theoretical model (blue)

Summary of farm simulation results (Farm layer height H_F = 280m, U_{F0} = 8.89 m/s), K_s is the momentum loss factor assigned to the support structure

Case	K_s	$C^*_{D(CFD)}$	$(A_s/A)C_D^*$
1	0	0	0
2	0.542	0.270	0.0321
3	1.129	0.448	0.0533
4	1.422	0.505	0.0600
5	1.716	0.537	0.0640
6	4	0.739	0.0879
7	5	0.774	0.0921



Time-averaged streamwise velocity [m/s] contours on a lateral plane across the centre of a turbine; dashed and solid lines show the rotor and tower positions, respectively.

$\tau_{w(0)}$: Wind-induced shear stress on the land/sea surface after (before) farm construction. S: Land/sea surface area per turbine. T: Turbine thrust. D: Support structure drag. $\Delta p/\Delta p_0$: Pressure gradient after/before wind farm construction. A: Rotor swept area. A_s: Frontal projected area of support structure. α: Local flow reduction factor (U_T/U_F). β: Farm flow reduction factor (U_F/U_{F0}). U_T: Average wind speed across A. $U_{F(0)}$: Average wind speed across wind farm layer after (before) farm construction. γ: Empirical parameter (typically 2). ζ: Environment-dependent empirical parameter. Λ: Farm density (A/S). C_{f0}: Natural friction coefficient of the land/sea surface

Conclusions and Future study:

- ❑ The support structures have an increasingly important influence on the overall performance of a very large wind farm as the farm density (or the number of turbines installed in a given farm area) increases.
- ❑ Optimal rotor resistance decreases and therefore the relative importance of support-structure drag increases as the farm density increases.
- ❑ The environment-dependent parameter "ζ" has a greater effect on wind farm performance than the support-structure drag
- ❑ Fully-resolved turbine model simulations will be carried out for further theoretical model improvement and a collaboration work with Met Office is undergoing to extensively investigate the environment-dependent parameter "ζ".

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