Investigation of wake impact of upstream wind turbine on downstream turbines' power generation

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AE703 Rotor Aerodynamics

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Introduction and Goal

- Wind turbines are designed to extract kinetic energy of the incoming flow which means that flow slows down downstream. This is a problem for downstream turbines in terms of power generation and blade loading.
- The National Renewable Energy Laboratory (NREL) found that majority of U.S. states requires turbines to be spaced no closer than 3 rotor diameters apart. In Europe, most countries requires at least 5 rotor diameters of spacing.
- How much does the velocity reduction affect Cp? Is 3 rotor diameter enough?

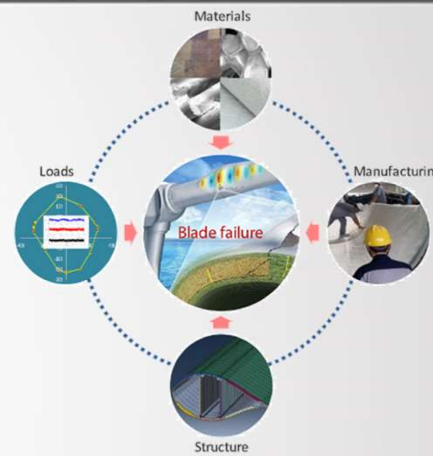


Fig 1. Causes of blade failure. [1]

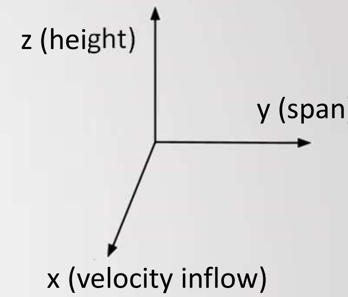
Fig 2. Structural failure of blade #a. [1]

[1] Chen, X. Fracture of wind turbine blades in operation—Part I: A comprehensive forensic investigation. *Wind Energy*. 2018; 21: 1046– 1063.

Validation and Test Cases

Validation Cases (Sexbierum Wind Farm [2] and [3])

- Case 1 & 2 - Single Wind Turbine with axial 5m/s and 10m/s inflow.
- Case 3 & 4 -Triple Wind Turbine aligned axially (5D apart) with axial 5m/s and 10m/s inflow.



Test Cases

- Case 1 Triple Wind Turbine aligned axially (3D apart) with axial 5m/s inflow.
- Case 2 Triple Wind Turbine aligned in a checkered pattern(5D apart) with axial 5m/s inflow.
- Case 3 Triple Wind Turbine aligned diagonally (5D apart) with axial 5m/s inflow.

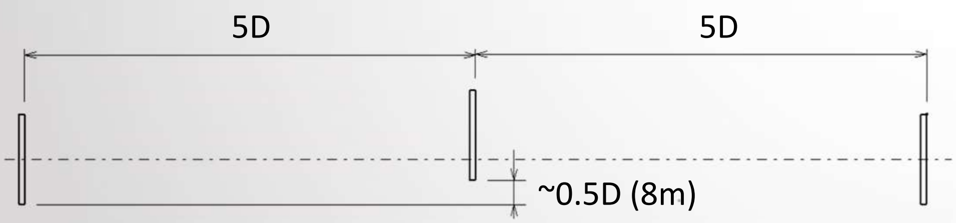


Fig 3. Test Case 2 diagram of turbine placement

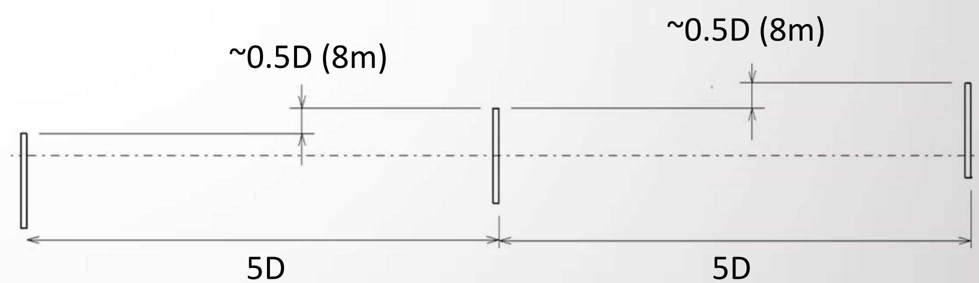


Fig 4. Test Case 3 diagram of turbine placement

[2] Cleijne JW, Results of the Sexbierum wind farm; double wake measurements, Technical Report 92-388, TNO Environmental and Energy Research, Apeldoorn, Netherlands, 1992.
[3] Cleijne JW, Results of the Sexbierum wind farm; single wake measurements, Technical Report 93-082, TNO Environmental and Energy Research, Apeldoorn, Netherlands, 1993.

Approach

- Wind turbines are not directly meshed instead it is modeled using actuator lines.
- Modelled using Large-Eddy Simulation. Turbulence intensity:

$$I_x = \frac{u'}{U_0} \quad I_y = \frac{v'}{U_0} \quad I_z = \frac{w'}{U_0}$$

- Goal is to quantify effects based on Coefficient of Power.

$$C_P = \frac{P_{out}}{0.5 * \rho * A * {U_0}^3}$$

- Added some extra details that complements class lectures.

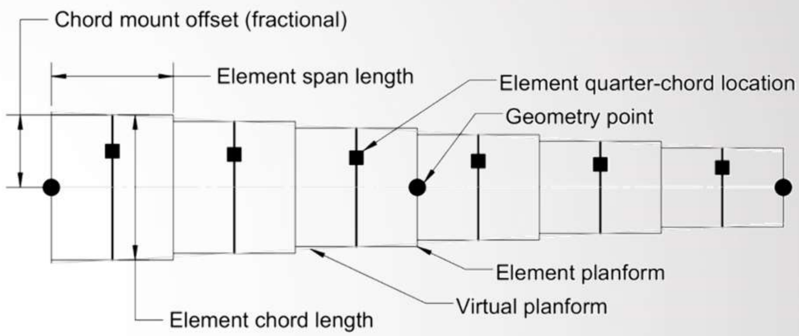


Fig 5. Actuator line geometry for turbineFoam. [4]

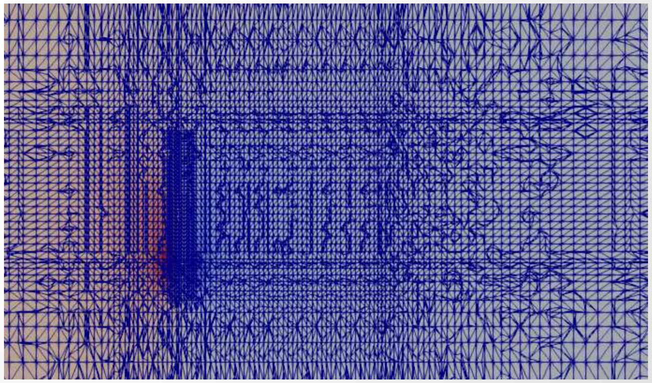


Fig 6. Section of mesh of Turbine 1 at midplane along y .

[4] Bachant, P., Goude, A., and Wosnik, M. (2016) Actuator line modeling of vertical-axis turbines.

Geometry and Boundary Conditions (BC)

Fig 7. Geometry of WPS 30/3 Wind Turbine

Table 1. Segment Blade Geometry

Segment	Radius (m)	Chord (m)	Twist (deg)
1	1.2693	0.696	11.1
2	2.2536	0.8105	11.1
3	3.2378	0.9245	11.1
4	4.2223	0.98	10.41
5	5.2067	0.9205	8.38
6	6.191	0.8615	6.35
7	7.1754	0.8025	4.33
8	8.1598	0.7435	2.85
9	9.1441	0.6845	2.22
10	10.1286	0.625	1.58
11	11.1128	0.5666	0.95
12	12.0972	0.5095	0.53
13	13.0815	0.4565	0.38
14	14.0659	0.4035	0.23
15	15.05	0.35	0.08

Table 2. Boundary Conditions for all simulations

Patch	BC for Velocity	BC for Pressure	BC for k (TKE)
Inlet	fixedValue (5 or 10)	zeroGradient	fixedValue (0.095)
Outlet	zeroGradient	fixedValue (0)	zeroGradient
Side and Top walls	slip	zeroGradient	fixedValue (0)
Bottom wall	slip	zeroGradient	fixedValue (0)

Workflow and Numerical Scheme

Workflow

1. Create blockMesh and refine mesh.
2. Create 0, system and constant files for OpenFOAM
3. Decompose mesh into equal 48 subdomains.
4. Submit job to WSU High Performance Computing (48 processors, 2 nodes, 96gb memory)
5. Reconstruct mesh and post-process in Paraview

Numerical Scheme

- Time Scheme: Euler (First-Order)
- Gradient Scheme: Gauss (Second-Order) Linear
- Divergent Scheme: Gauss Upwind (First-Order)
- Laplacian Scheme: Gauss (Second-Order) Linear
- pimpleFOAM solver
  1 outer corrector loop
  2 inner corrector loop
- Simulation Type: LES using Smagorinsky model. Default coefficient.

Validation Case 1 and 2

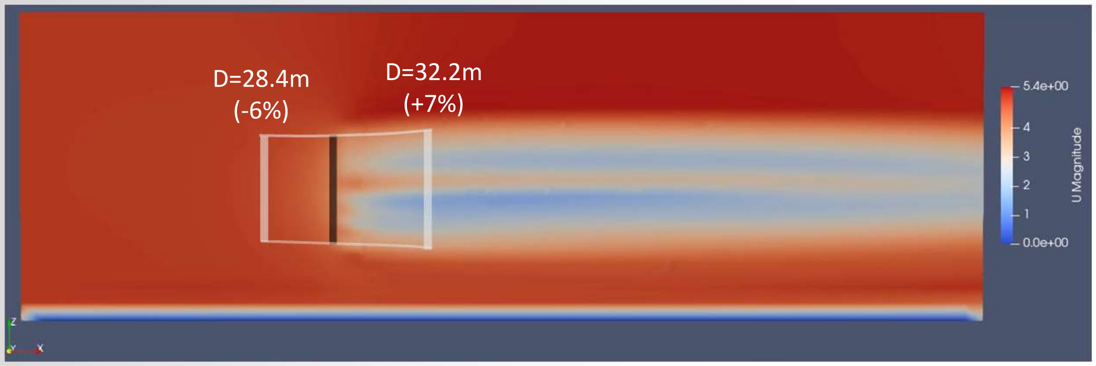


Fig 8. Velocity at the midplane along y for Validation Case 1 (60s – 90s).

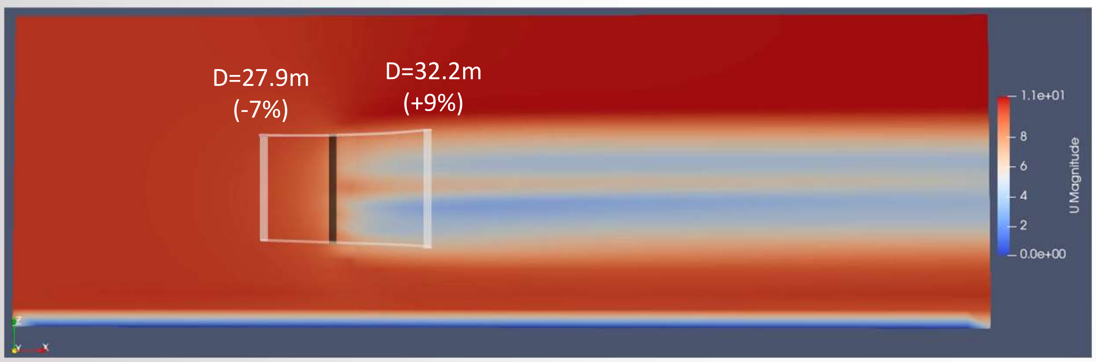


Fig 9. Velocity at the midplane along y for Validation Case 2 (60s – 90s).

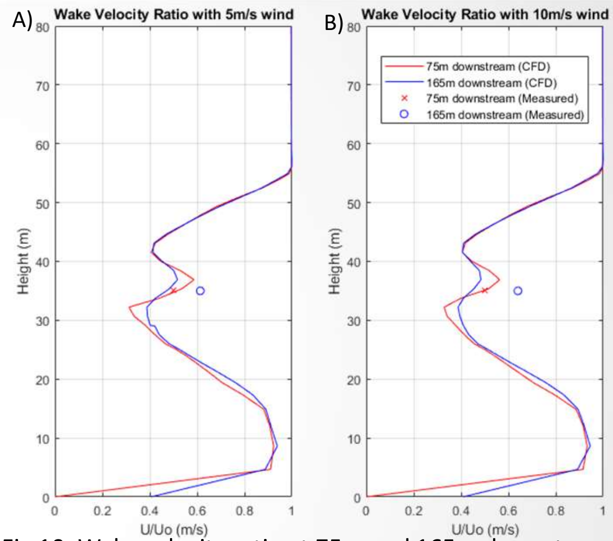


Fig 10. Wake velocity ratio at 75m and 165m downstream of Turbine 1 (90s)
A) Validation Case 1 B) Validation Case 2

Table 3. Comparison of CFD and measured Cp and axial interference factor with manufacture's rating for Validation Case 1 & 2.

Wind Speed	CFD		Measured		Manufacturer's rating	
	Cp	a	Cp	a	Cp	a
5m/s	0.35	0.11	0.36	0.11	0.36	0.11
10m/s	0.41	0.14	0.44	0.15	0.38	0.12

Note: CFD Cp is the average Cp from 30s-90s and measured Cp is the average Cp for 90s of measurements.

Validation Case 3 and 4

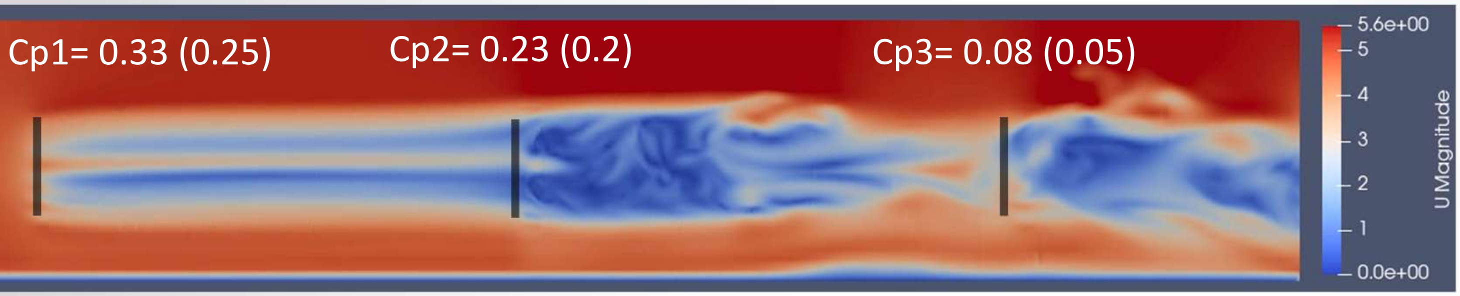


Fig 11. Velocity at midplane along y of Validation Case 3 (120s-180s). Reported is the Cp from CFD and in parenthesis, the measured Cp. Cp from CFD was taken as the average Cp over 90s-180s interval while measured Cp was the average of 90s of measurements.

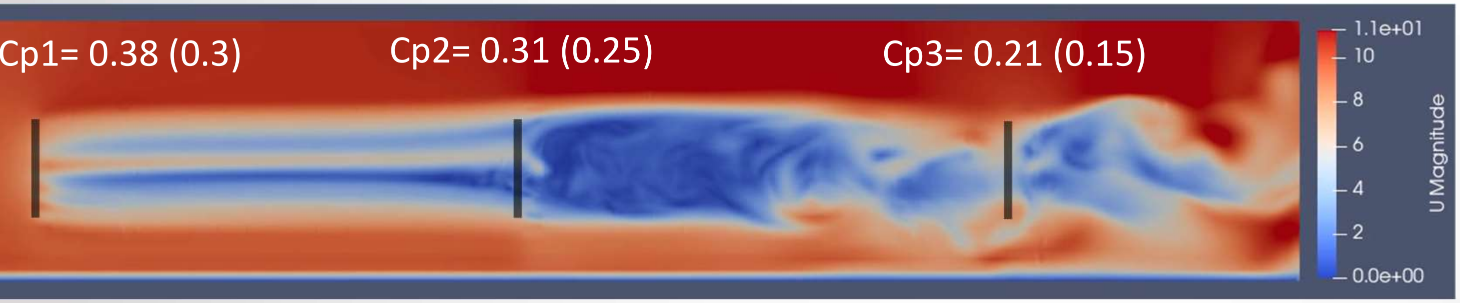


Fig 12. Velocity at midplane along y of Validation Case 4 (120s-180s).

Table 4. Comparison of CFD and measured Cp reduction of Turbine 2 and 3 for Validation Case 3 & 4.

Wind Speed	CFD Cp/Cp1	Measured Cp/Cp1
Turbine 2		
5m/s	0.75	0.8
10m/s	0.81	0.83
Turbine 3		
5m/s	0.24	0.2
10m/s	0.55	0.5

Validation Case 3 and 4

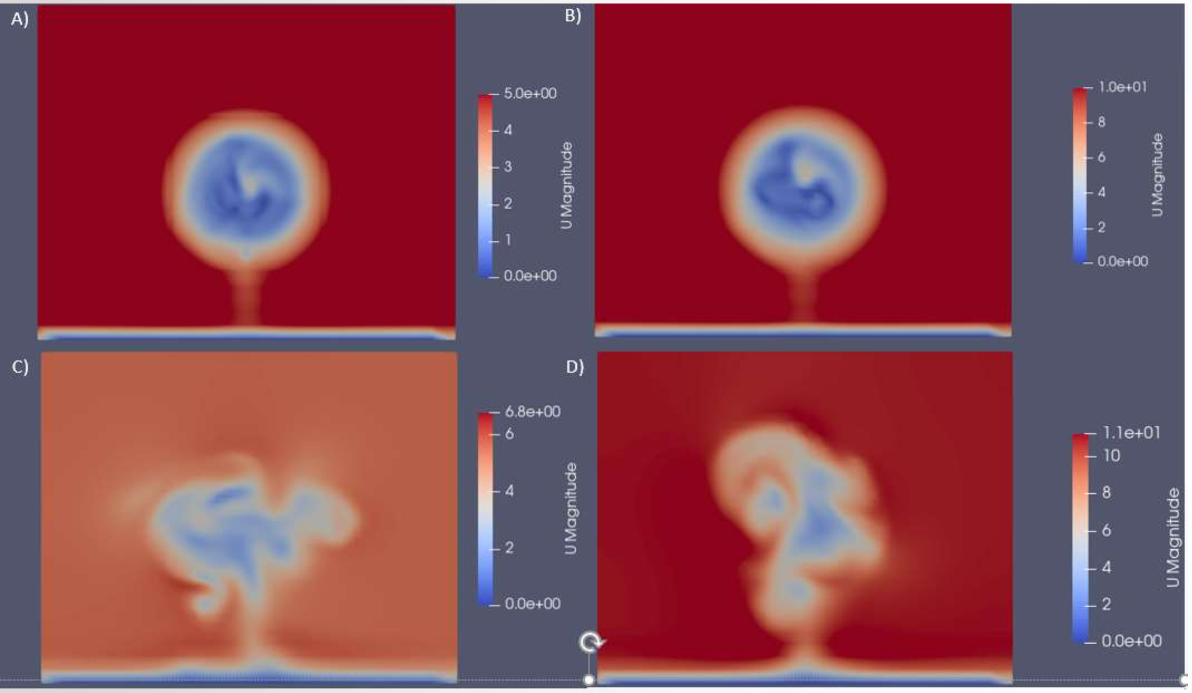


Fig 13. Inlet velocity 5m from Turbine 2 for A) Validation Case 3 and B) Validation Case 4 and Turbine 3 for C) Validation Case 3 and D) Validation Case 4 (120s).

Table 5. Comparison of average inlet velocity and non-dimensional inlet velocity 5m from Turbine 2 and 3 for Validation Case 3 and 4.

Wind Speed	$\bar{U}$	$\bar{U}/U_0$
Turbine 2		
5m/s	3.38 m/s	0.68
10m/s	7.14 m/s	0.71
Turbine 3		
5m/s	2.05 m/s	0.41
10m/s	4.31 m/s	0.43

Test Case 1

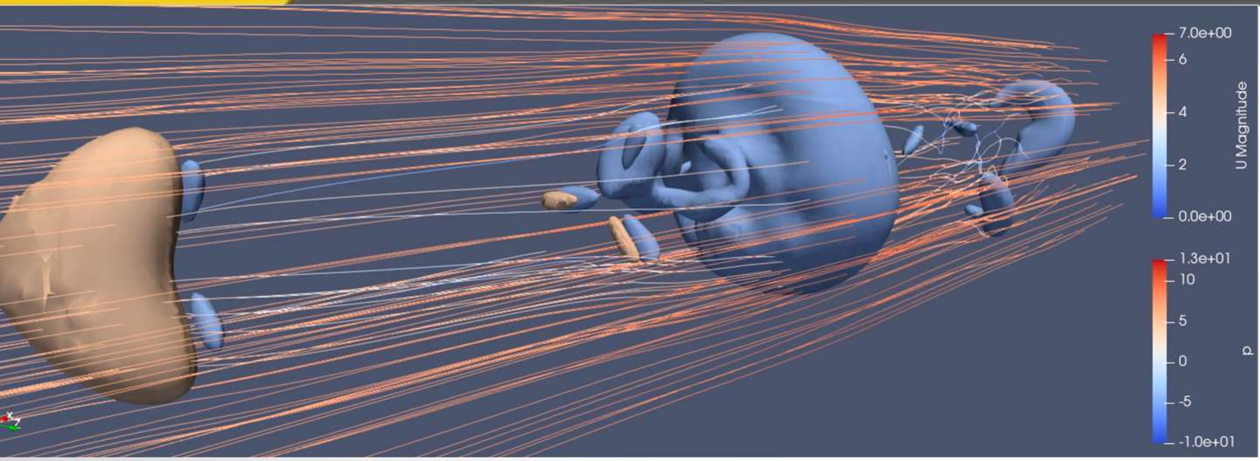


Fig 14. Streamline and Pressure Isosurface of -8 Pa of Test Case 1 (90s-180s).

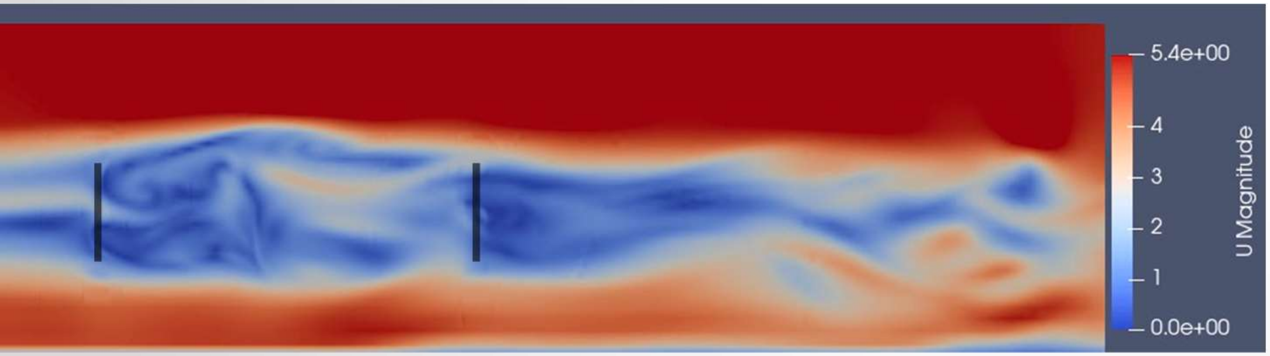


Fig 15. Velocity at midplane along y of Test Case 1 (90s-180s).

Table 8. Comparison of turbines' Cp, average inlet and average axial velocity with Validation Case 3.

		Cp	$\bar{U}$	$\bar{u}$
Turbine 2	Validation Case 3	0.24	3.38 m/s	3.3m/s
	Test Case 1	0.09	3.4 m/s	3.1 m/s
Turbine 3	Validation Case 3	0.08	2.05 m/s	1.9m/s
	Test Case 1	0.04	2.2 m/s	1.8 m/s

Table 9. Comparison of turbulent intensity 5m from the turbines with Validation Case 3.

		u'/U_0	v'/U_0	w'/U_0
Turbine 2	Validation Case 3	0.055	0.102	0.004
	Test Case 1	0.081	0.115	0.011
Turbine 3	Validation Case 3	0.082	0.121	0.055
	Test Case 1	0.185	0.256	0.086

Test Case 2 and 3

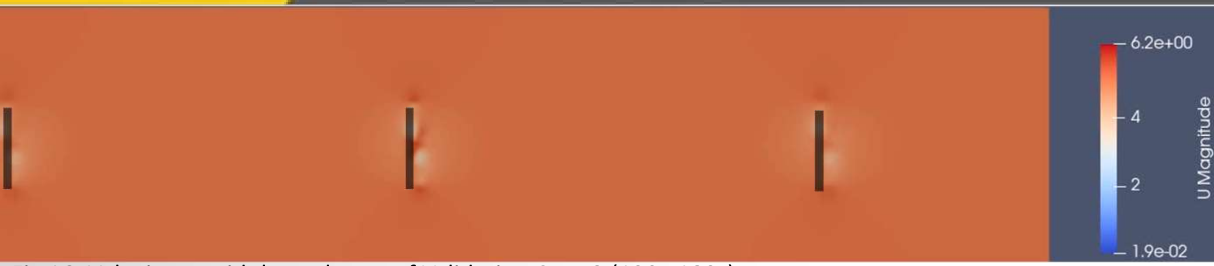


Fig 16. Velocity at midplane along z of Validation Case 3 (120s-180s).

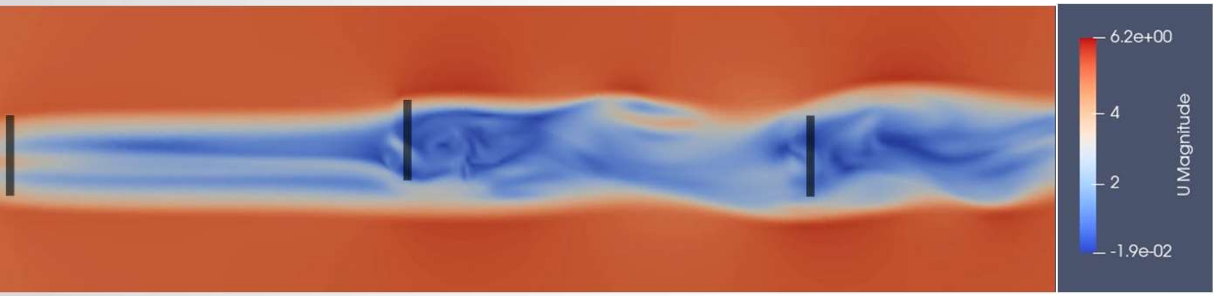


Fig 17. Velocity at midplane along z of Test Case 2 (120s-180s).

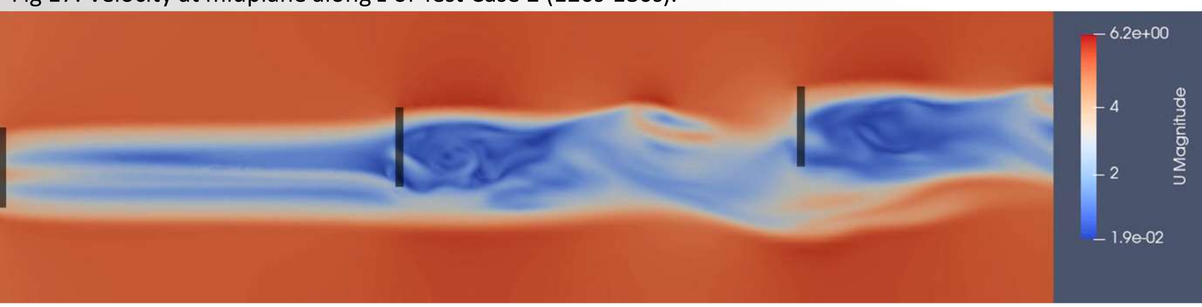


Fig 18. Velocity at midplane along z of Test Case 3 (120s-180s).

Table 11. Comparison of Cp, average inlet and average axial velocity for Turbine 2 with different turbine arrangements.

	Cp	$\bar{U}$	$\bar{u}$
Validation Case 3	0.23	3.38 m/s	3.3m/s
Test Case 2	0.22	3.4 m/s	3.3 m/s
Test Case 3	0.21	3.4m/s	3.25m/s

Table 12. Comparison of Cp, average inlet and average axial velocity for Turbine 3 with different turbine arrangements

	Cp	$\bar{U}$	$\bar{u}$
Validation Case 3	0.08	2.05 m/s	1.9m/s
Test Case 2	0.15	2.1m/s	2.05 m/s
Test Case 3	0.19	2.3m/s	2.2 m/s

Test Case 2 and 3

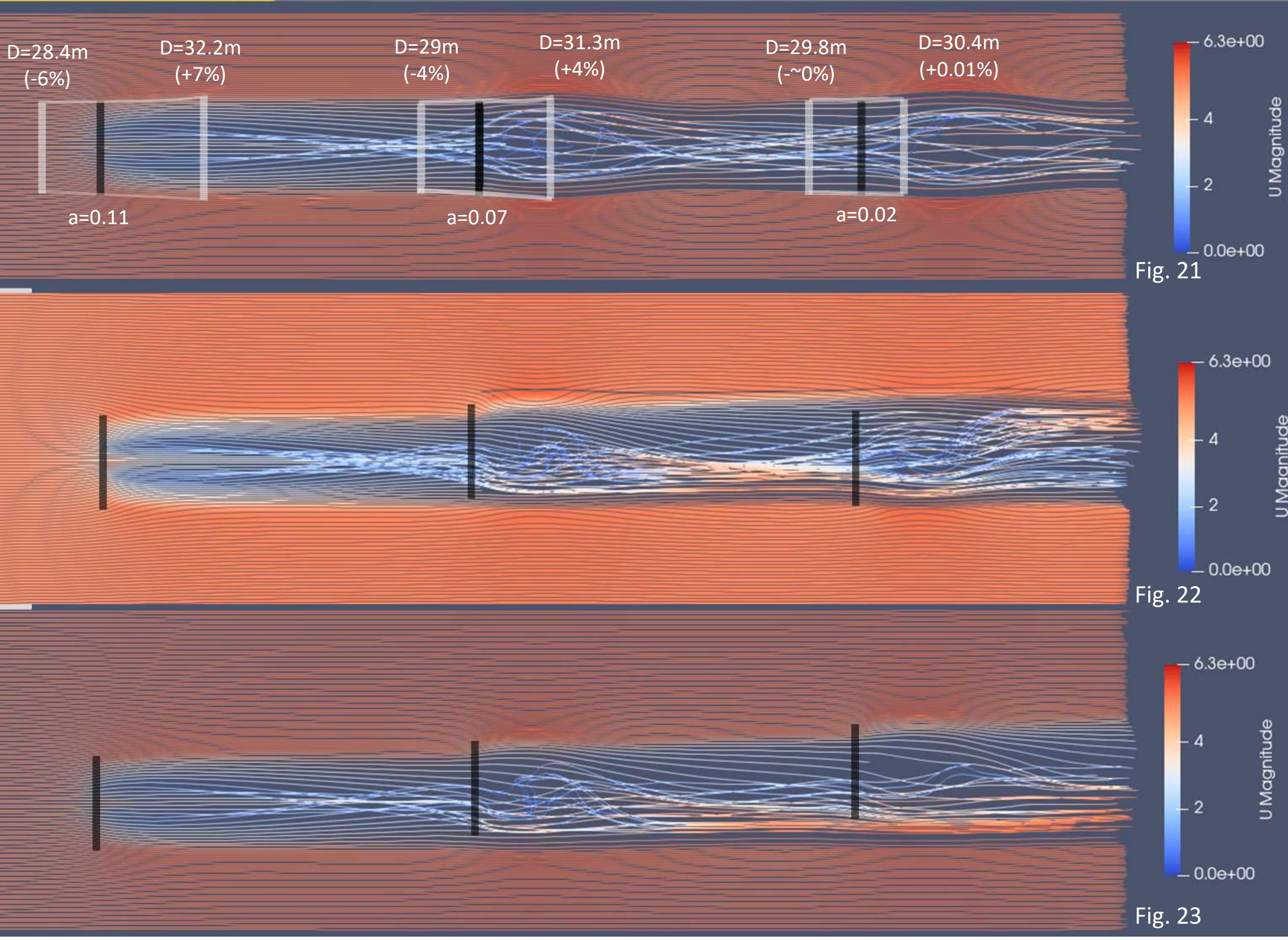


Fig. 21

Fig. 22

Fig. 23

Fig 19 Streamlines at midplane along z of Validation Case 3 (60s-120s).
Fig 20. Streamlines at midplane along z of Test Case 2 (60s-120s).
Fig 21. Streamlines at midplane along z of Test Case 3 (60s-120s).

Table 13. Comparison of Turbulent intensity 5m from Turbine 2 with different turbine arrangements.

	u'/U_0	v'/U_0	w'/U_0
Validation Case 3	0.055	0.102	0.004
Test Case 2	0.061	0.115	0.011
Test Case 3	0.064	0.092	0.009

Table 14. Comparison of Turbulent intensity 5m from Turbine 3 with different turbine arrangements.

	u'/U_0	v'/U_0	w'/U_0
Validation Case 3	0.082	0.121	0.055
Test Case 2	0.081	0.112	0.048
Test Case 3	0.111	0.158	0.062

Conclusion

- Most wind farm state ordinance in the U.S. are unreliable and to increase turbine's lifetime power production, care must be taken on wind turbine placement.
- Wake can have a big impact on the power production of downstream turbines due to velocity deficit . The severity depends on the spacing and arrangement between turbines.
- Optimization must be done to evaluate the best turbine arrangements given the space and wind direction. However, this is difficult and expensive to predict for a full wind farm (30hr just for 3 turbines!).
- For small scale wind farm (<10 turbines), it may be sufficient to space turbines 7D apart and arrange the downstream turbine in a checkered way.
- Even though this investigation shows that turbulent intensity have a small impact on Cp, studies show that turbulent intensity has a large impact on noise and blade fatigue.

Fig 22. Section of Waverly wind farm. [3]

Fig 2. Section of Meridian Wave wind farm. [3]

[5] U.S. Wind Turbine Database, October 2022.