Evolution of the wake of a floating wind turbine under imposed motion and mild turbulent conditions: a wind tunnel study

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WESC 2023 Conference - Glasgow, 24/05/2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement N° 860879.

Wake of floating wind turbines

❑ Motions of a FOWT

- Wave driven (f_p~0.1Hz)
- Natural period in translation (f_p~0.03 Hz)
- Natural period in rotation (f_p~0.01Hz)

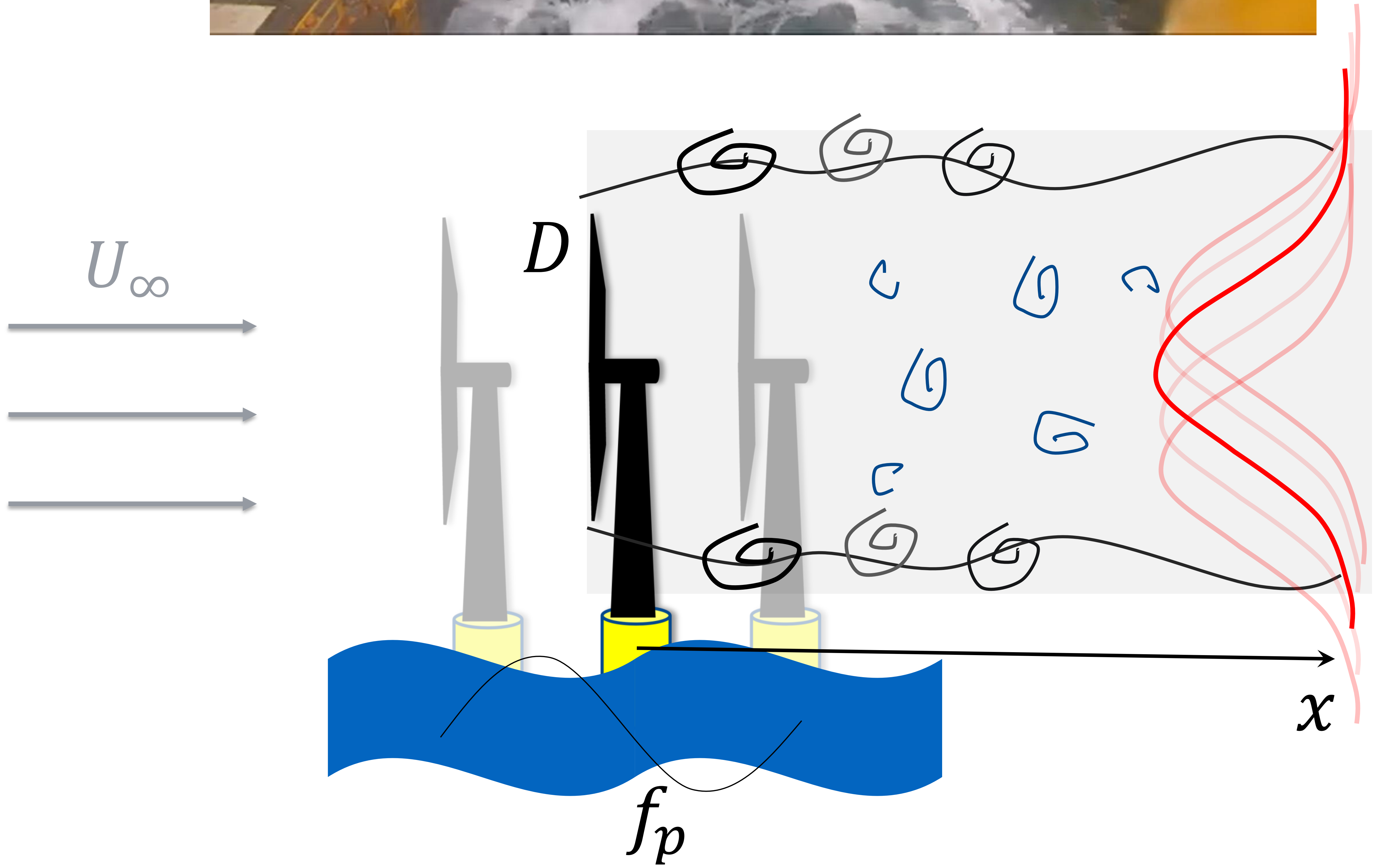
Roberston et al. (2014)
Leimester et al. (2018)

❑ How these movements impact the wake?

- Recovery
- Transition to far-wake (gaussian profile)
- Wake dynamics

Schliffke et al. (2020)
Li et al. (2022)

$$St = \frac{f_p D}{U_\infty}$$



Wind tunnel testing with a model FOWT

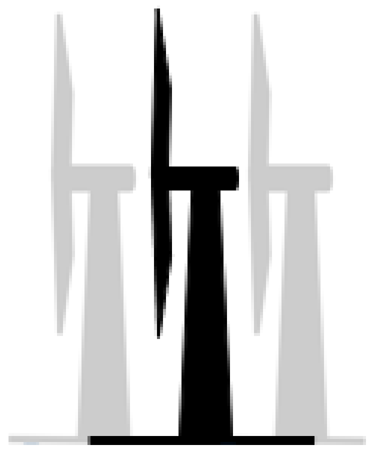
- **Model turbine Oldenburg 0.6 on a 6-DoF platform**
  - Reproduce motions of a floating turbine
  - Wake measurements, 2D to 10D
  - Hot-wires (1d in Oldenburg and 3d in Milan)

Messmer et al. (2022)

$$St = \frac{f_p D}{U_\infty}$$

- **Imposed 1DoF sinusoidal motions**
  - Fixed
  - Sway with St ≈ 0.38, A~0.01D
  - Sway with St ≈ 0.38, A~0.01D
  - $C_T \approx 0.85$
  - $U_\infty \approx 5$ m/s -> Re ≈ 2.10^5

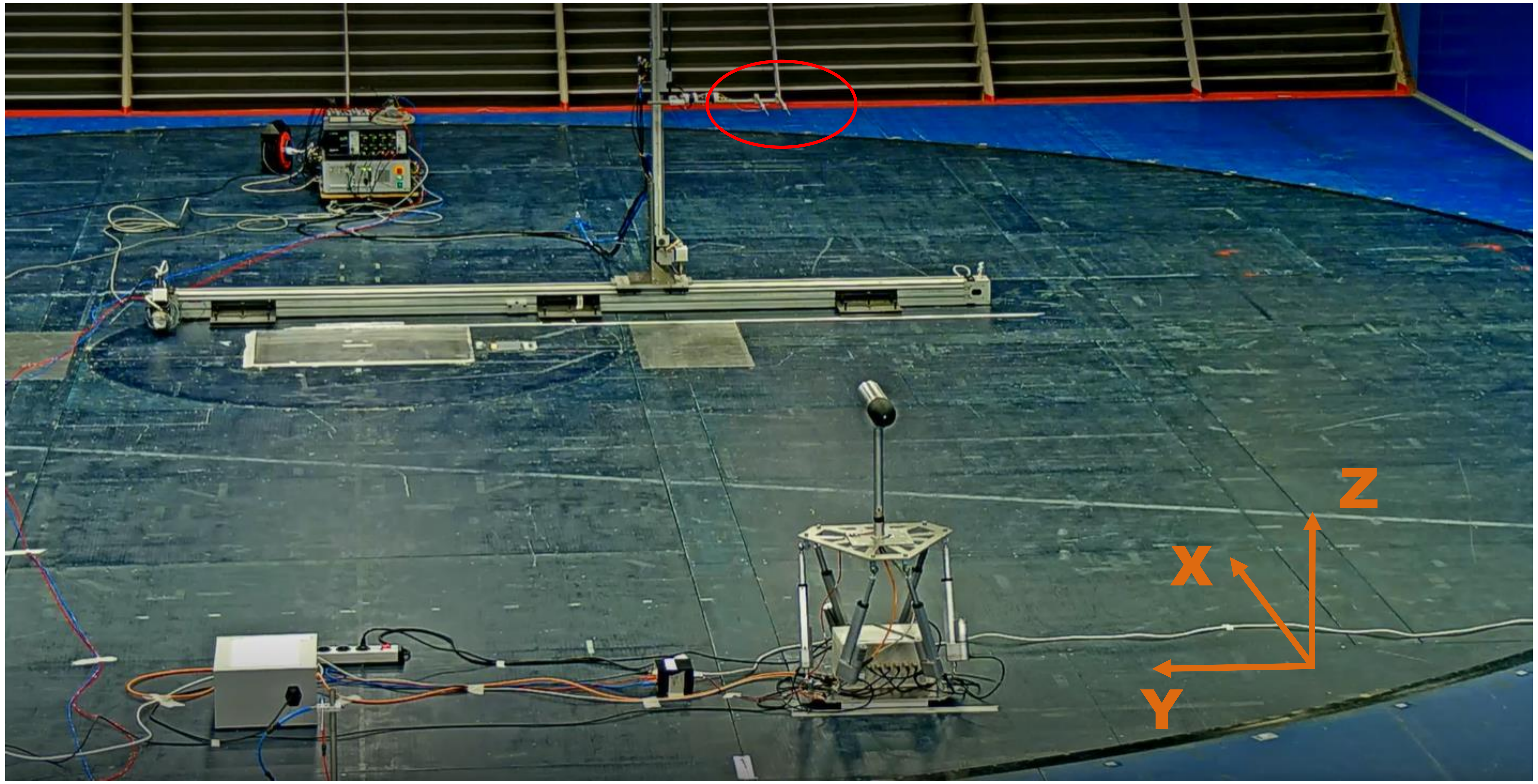
Sway



Surge

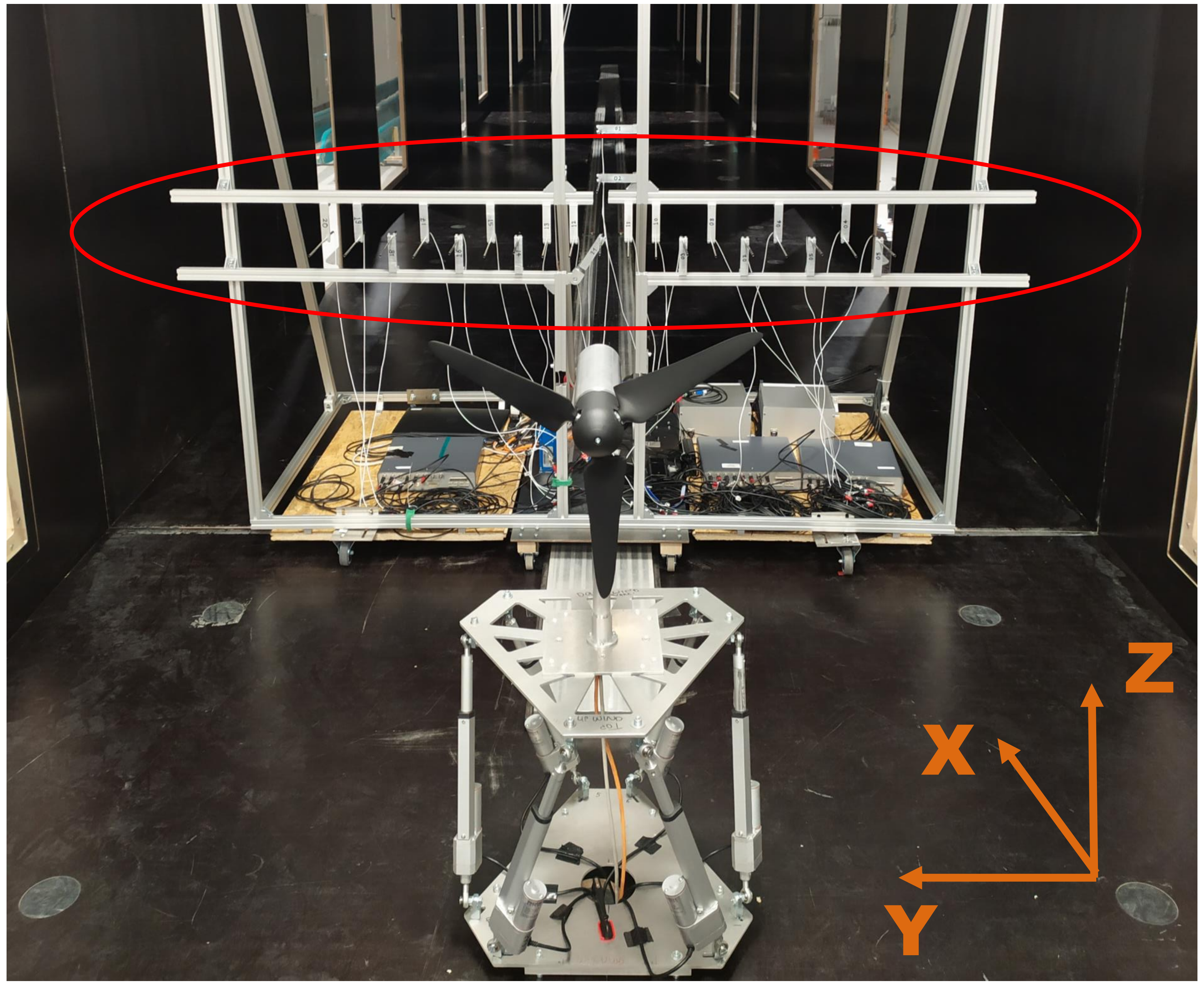
Experimental set-up

Milan



Background TI$_\infty$ ≈ 1.5%

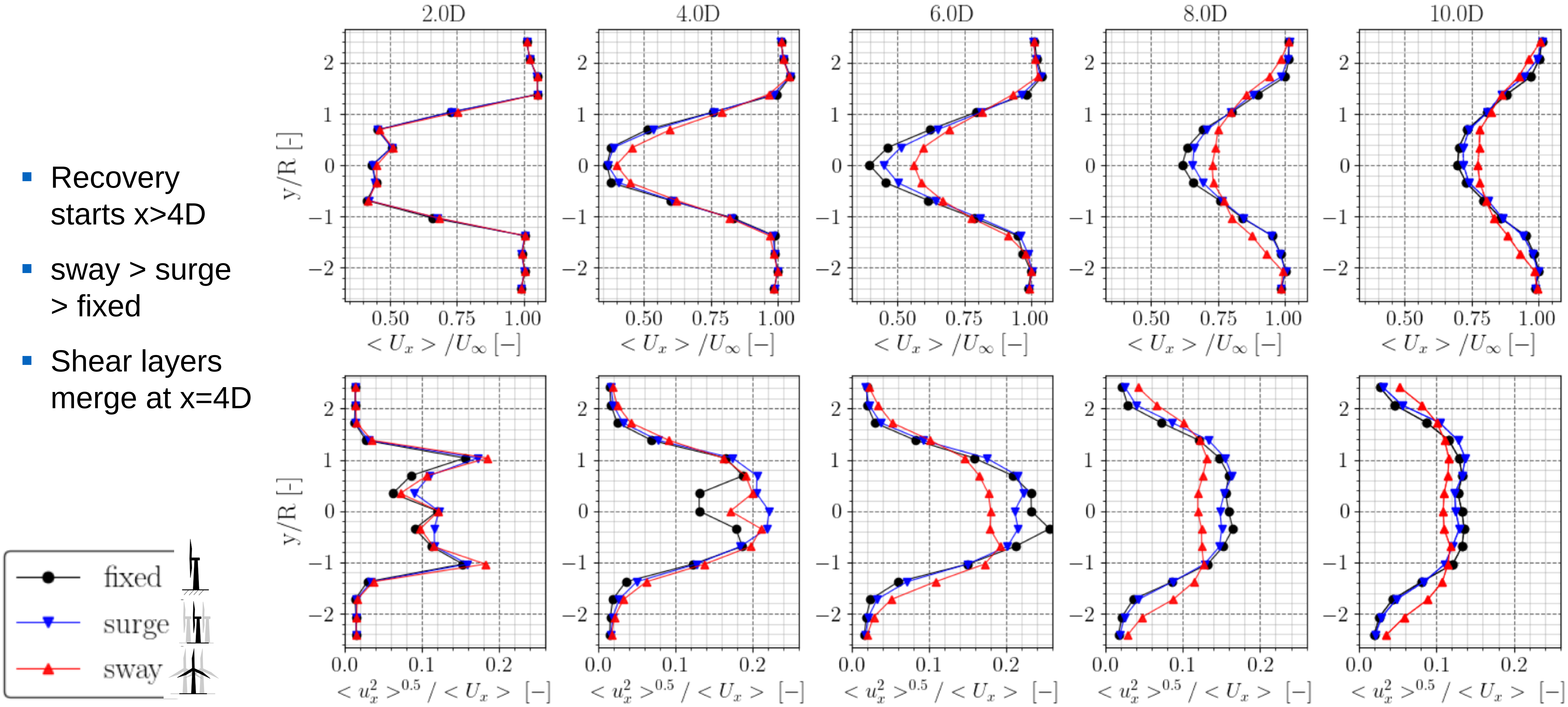
Oldenburg



Background TI$_\infty$ ≈ 0.3%

Wake speed and TI profiles at hub height (Milan, $TI_\infty \approx 1.5$ %)

- Recovery starts x>4D
- sway > surge > fixed
- Shear layers merge at x=4D



 @ForWind_DE

FLOAWER FLOAting Wind Energy netwoRk

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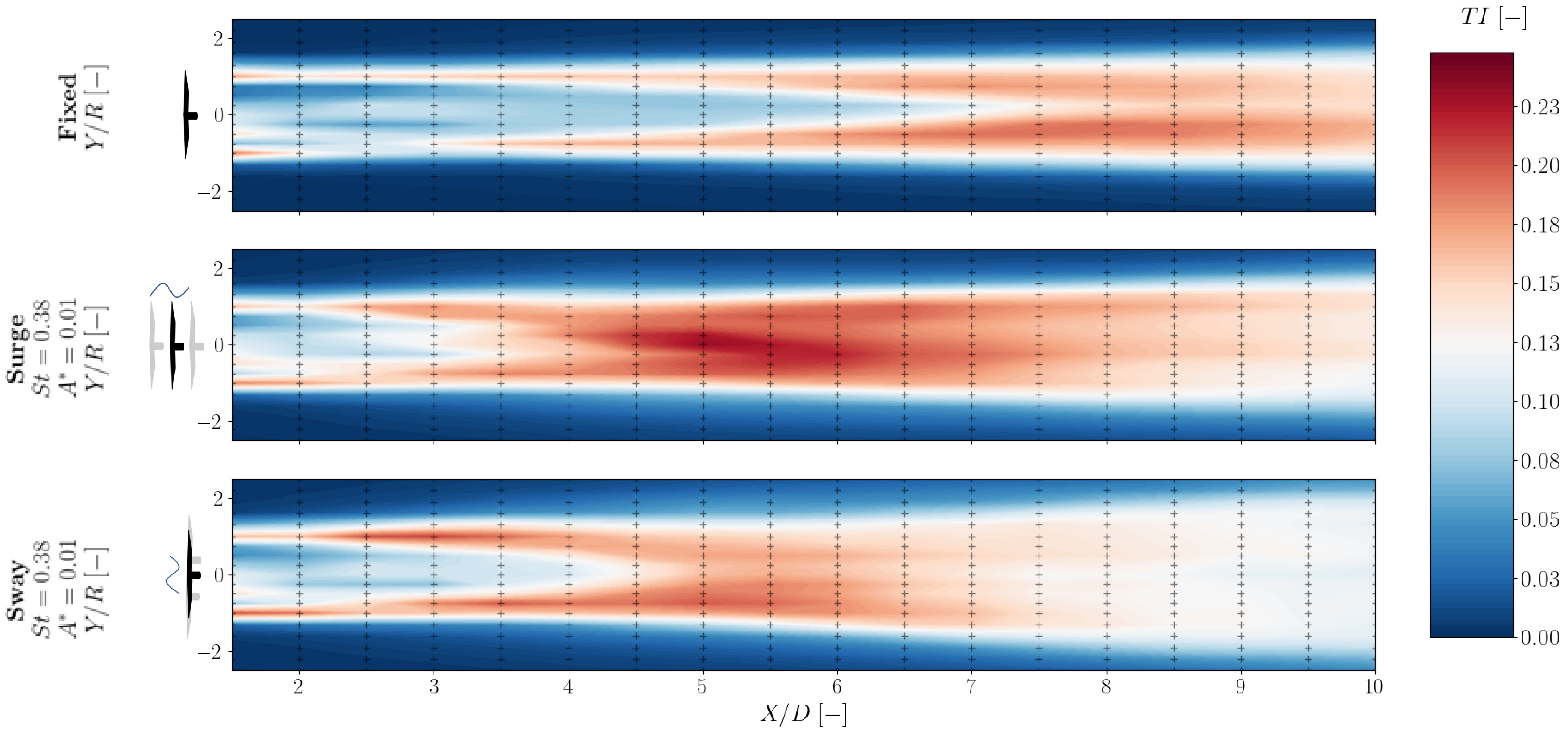
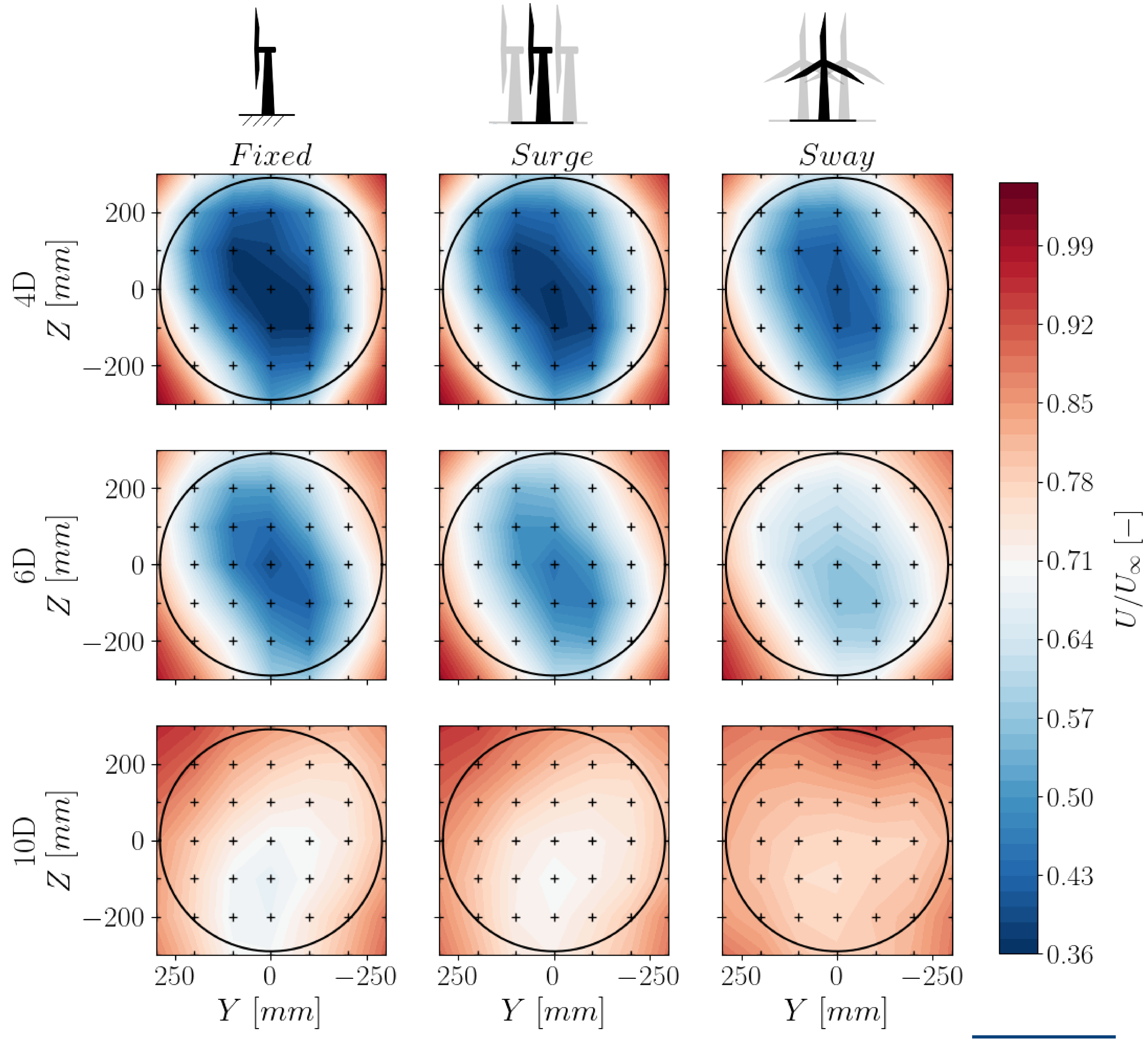
Color map of TI (Oldenburg, $TI_\infty \approx 0.3$ %)

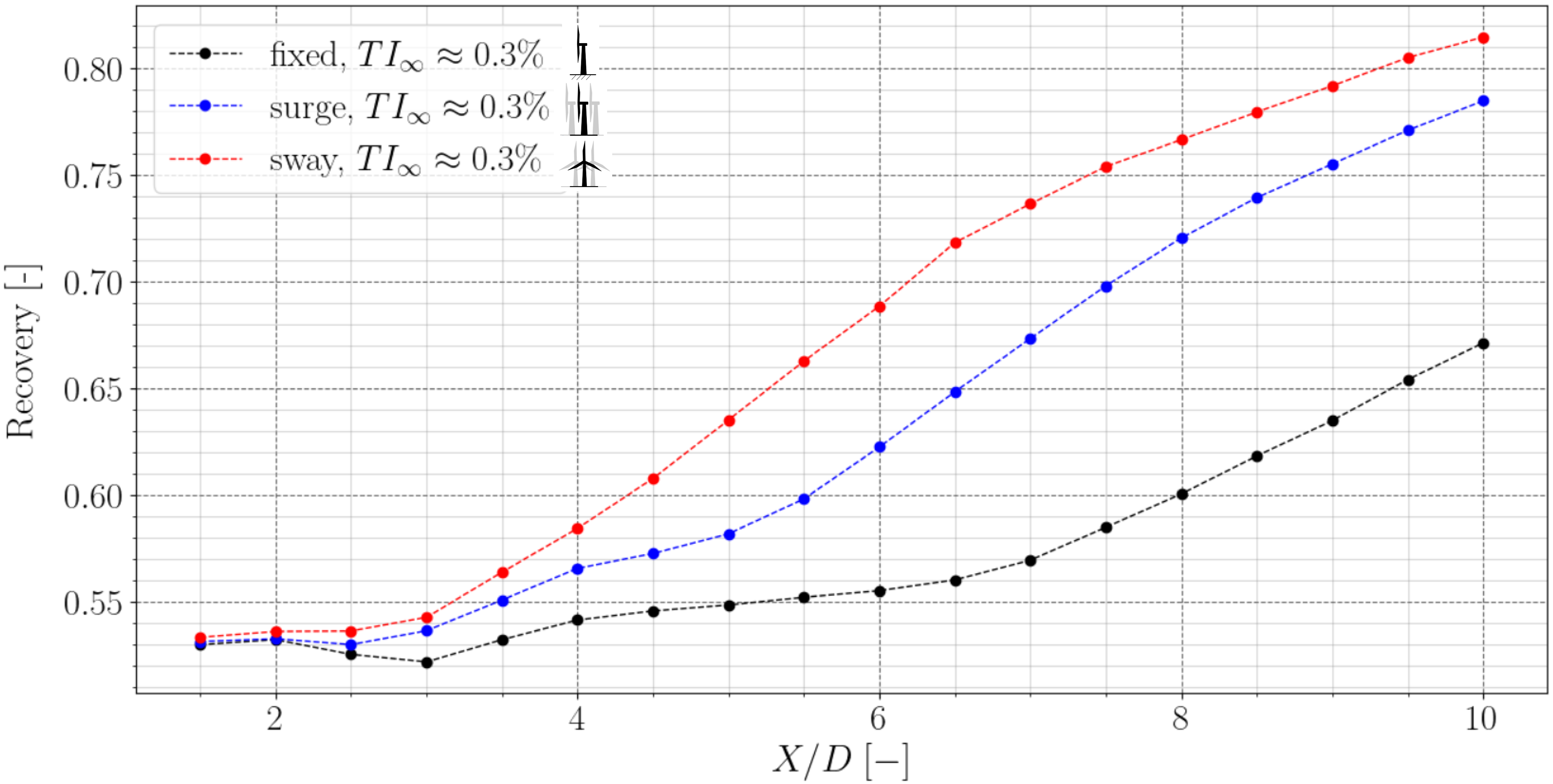


Wake wind speed map (Milan, $TI_\infty \approx 1.5$ %)

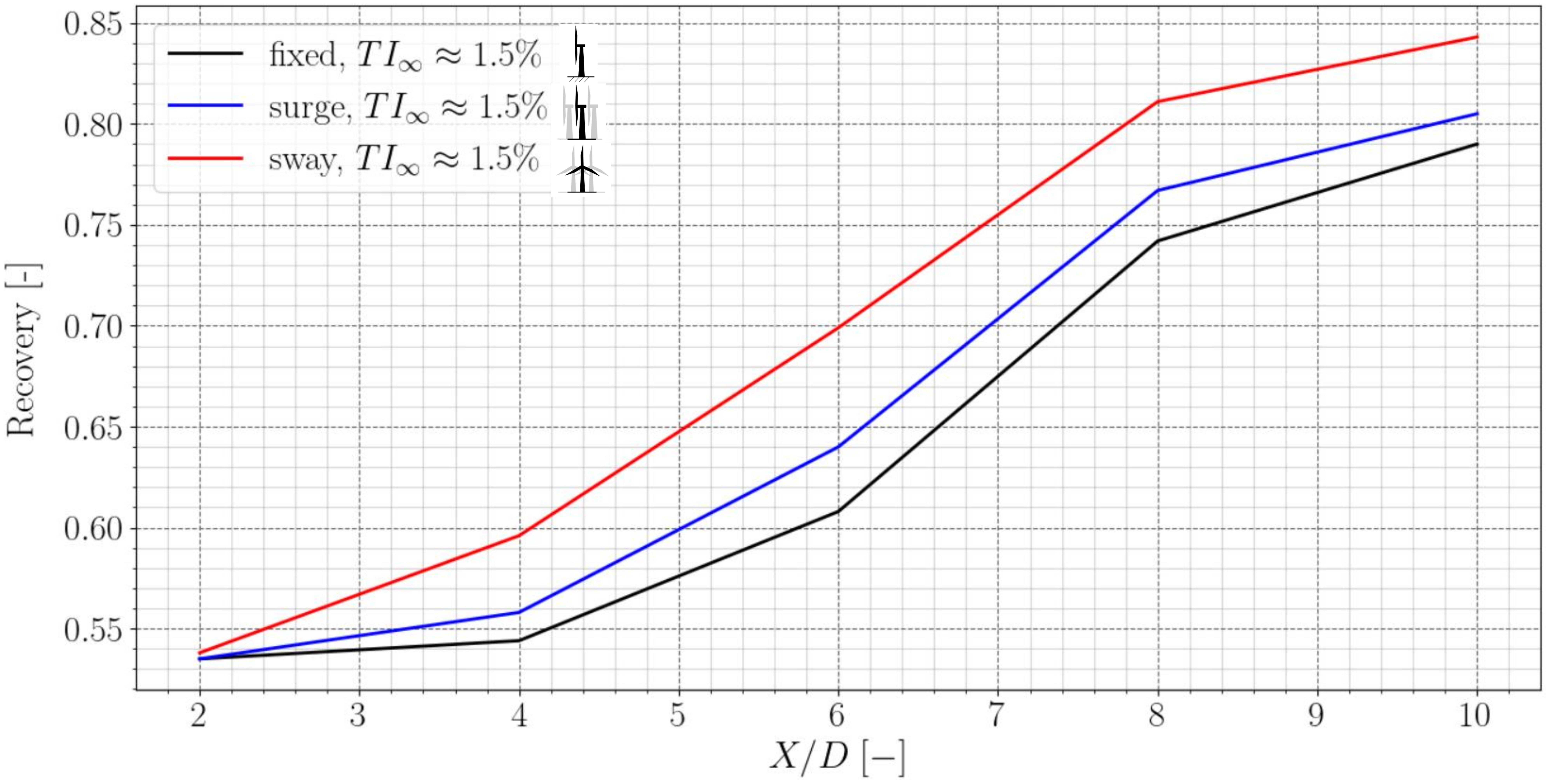
- Wake starts to recover at 4D
- Integration of the average wind speed in rotor area
-> recovery
- Power available for a downstream turbine



Recovery vs. X/D (Oldenburg, TI_∞ ≈ 0.3 %)

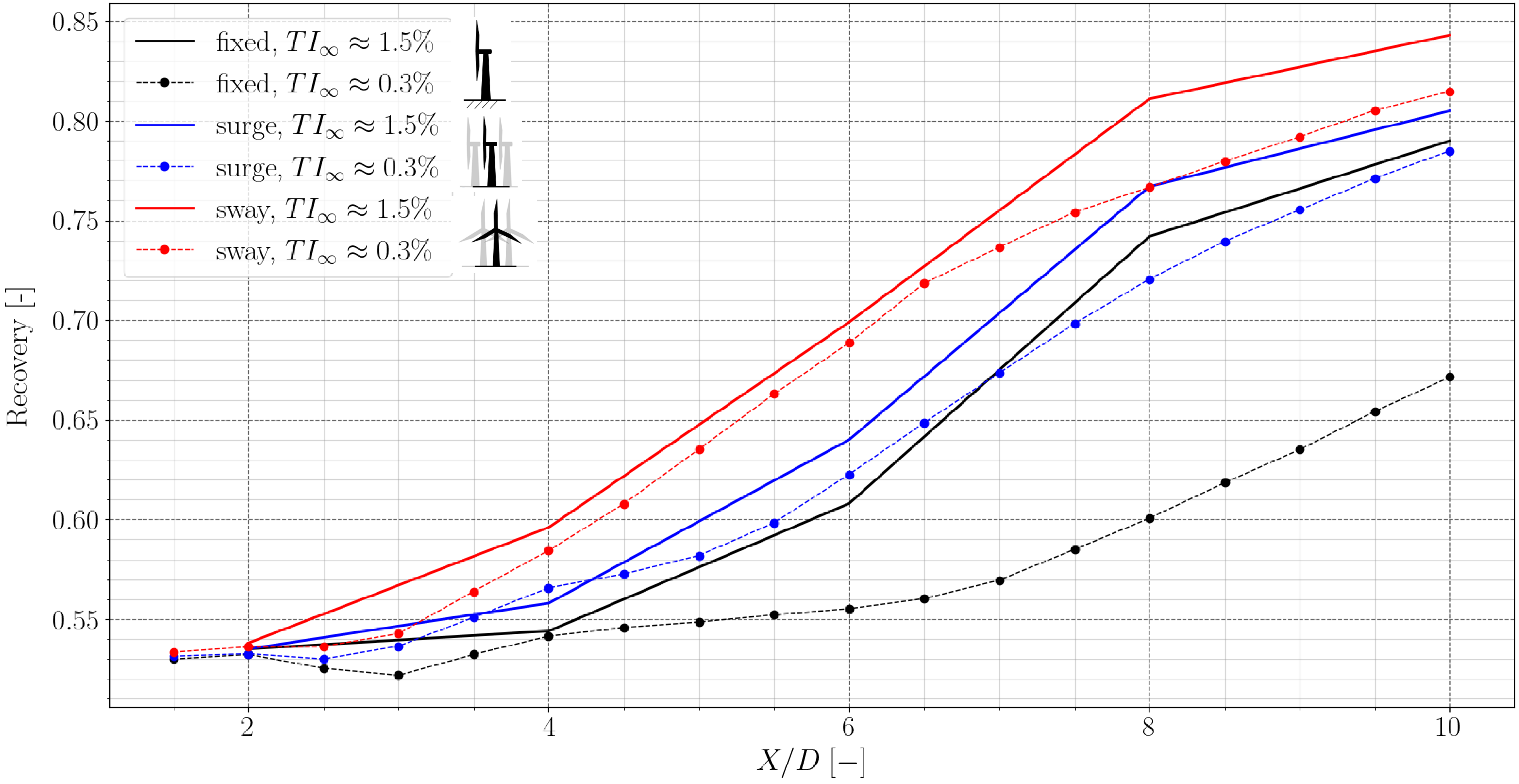


Recovery vs. X/D (Milan, $TI_\infty \approx 1.5$ %)



Recovery vs. X/D (Milan and Oldenburg)

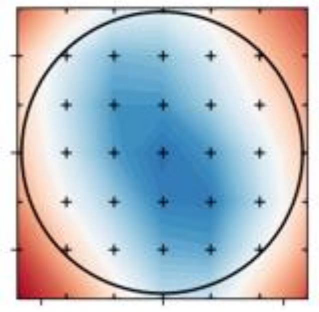
- Significant differences for fixed between $TI_\infty \approx 0.3\%$ and $TI_\infty \approx 1.5\ \%$
- Effect of inflow turbulence seems more significant than movements
- Nevertheless, motions enable faster recovery



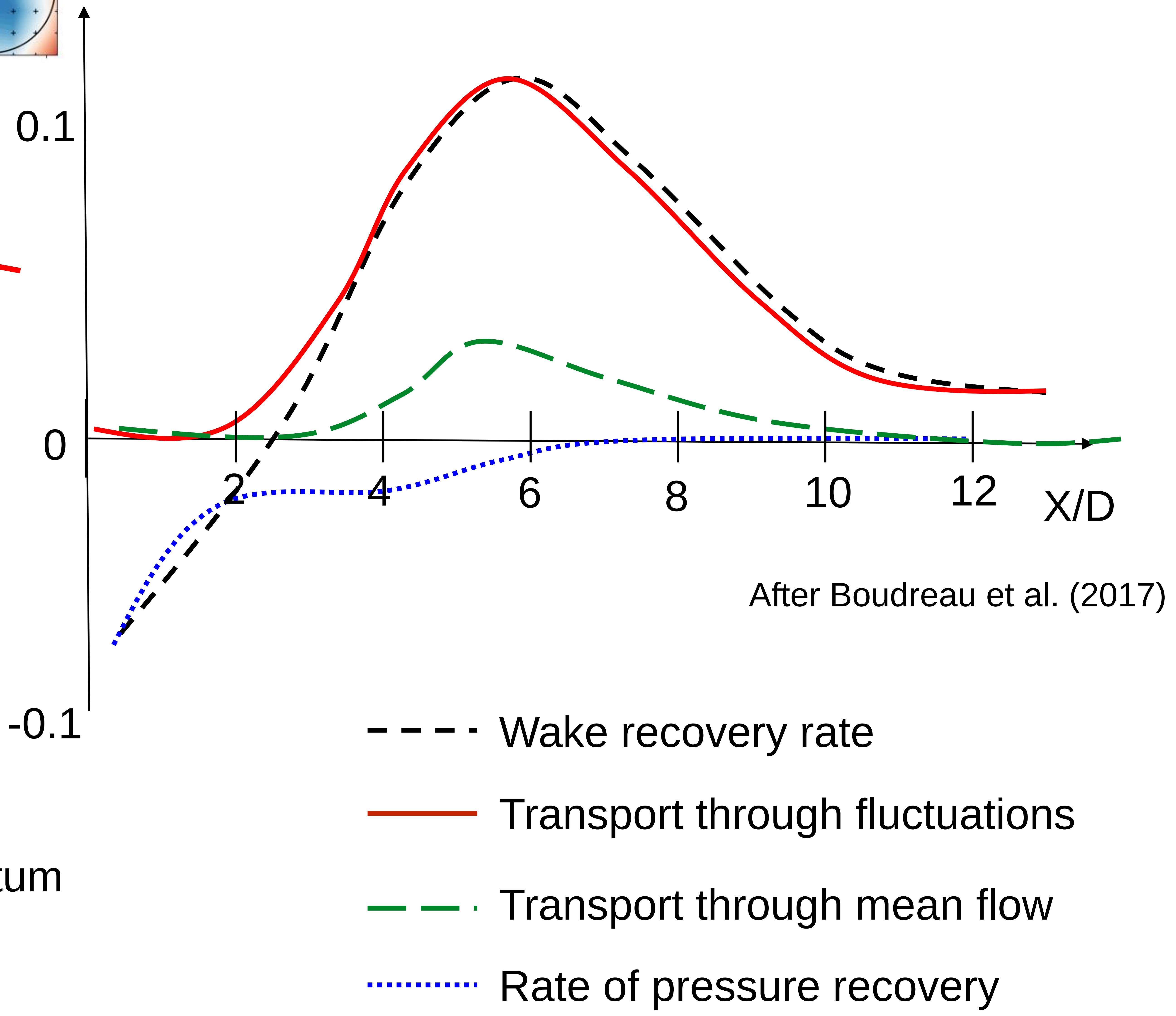
What are the mechanisms that play a role in the wake recovery process?

Wake recovery rate equation

Average over rotor

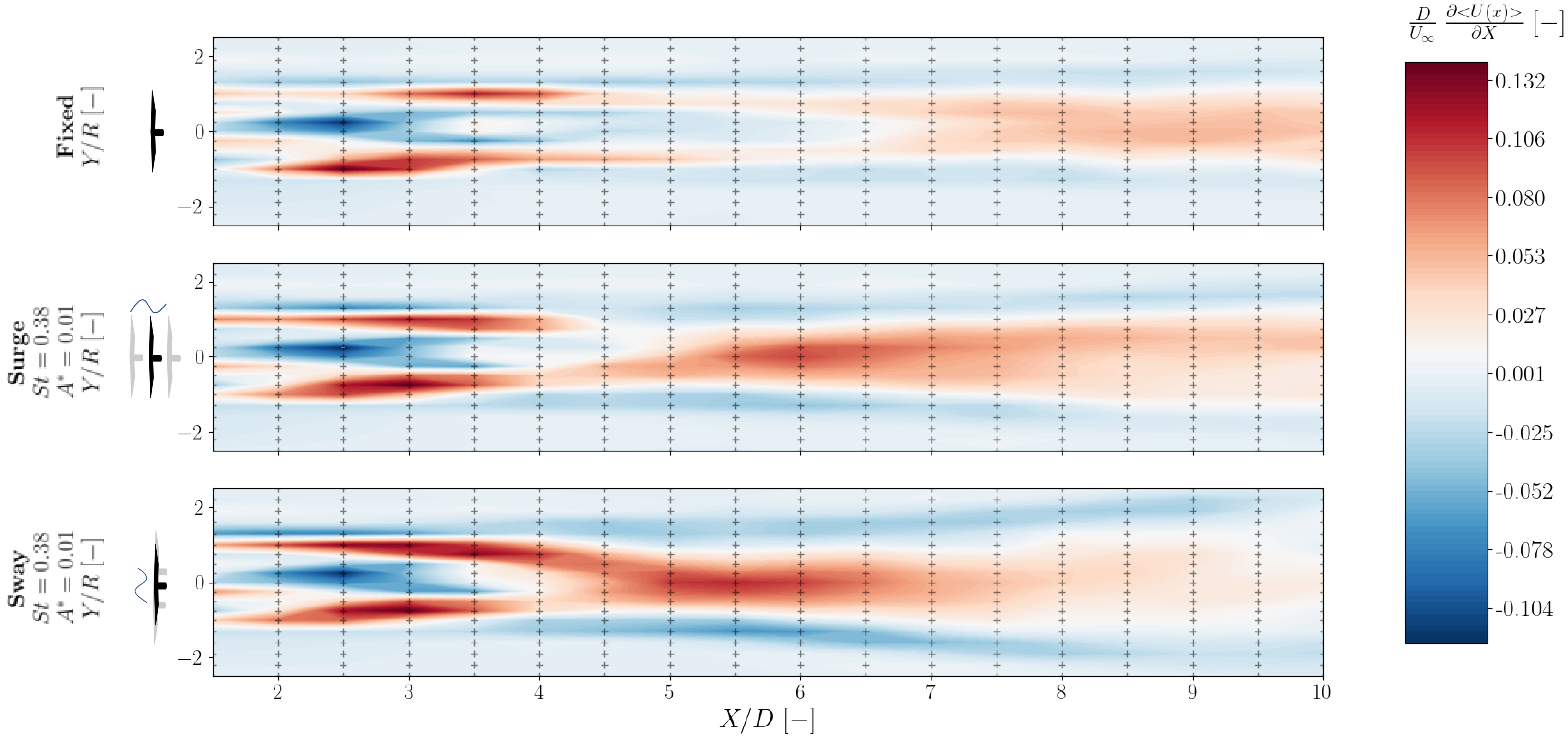


$$\frac{D}{U_\infty}\frac{\partial \overline{U}}{\partial x} = \frac{D}{U_\infty}\frac{1}{\overline{U}}\Bigg[-\overline{V}\frac{\partial \overline{U}}{\partial y} - \overline{W}\frac{\partial \overline{U}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{P}}{\partial x} - \frac{\partial \overline{(U'\,U')}}{\partial x} - \frac{\partial \overline{(U'\,V')}}{\partial y} - \frac{\partial \overline{(U'\,W')}}{\partial z} + 2\,\frac{\partial(\overline{\nu_t}\,\overline{S_{1j}})}{\partial x_j} + 2\,\frac{\partial(\overline{\nu'_t\,S'_{1j}})}{\partial x_j} + \nu\frac{\partial^2 \overline{U}}{\partial x_j\, x_j}\Bigg].$$

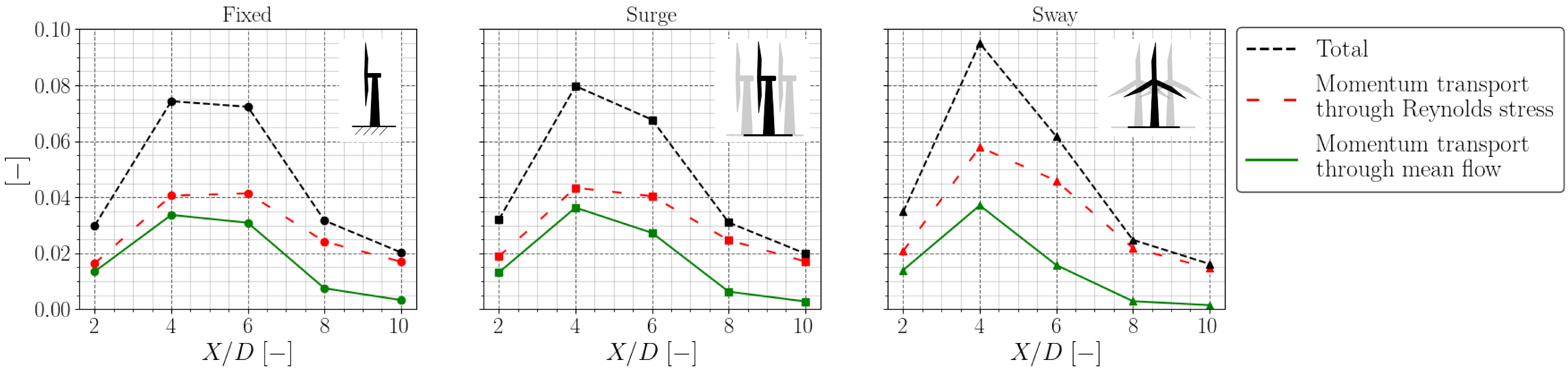


- RANS equation in the streamwise direction
- Tells about the exchange and transport of momentum within the wake

Wake recovery rate (Oldenburg, $TI_\infty \approx 0.3$ %)



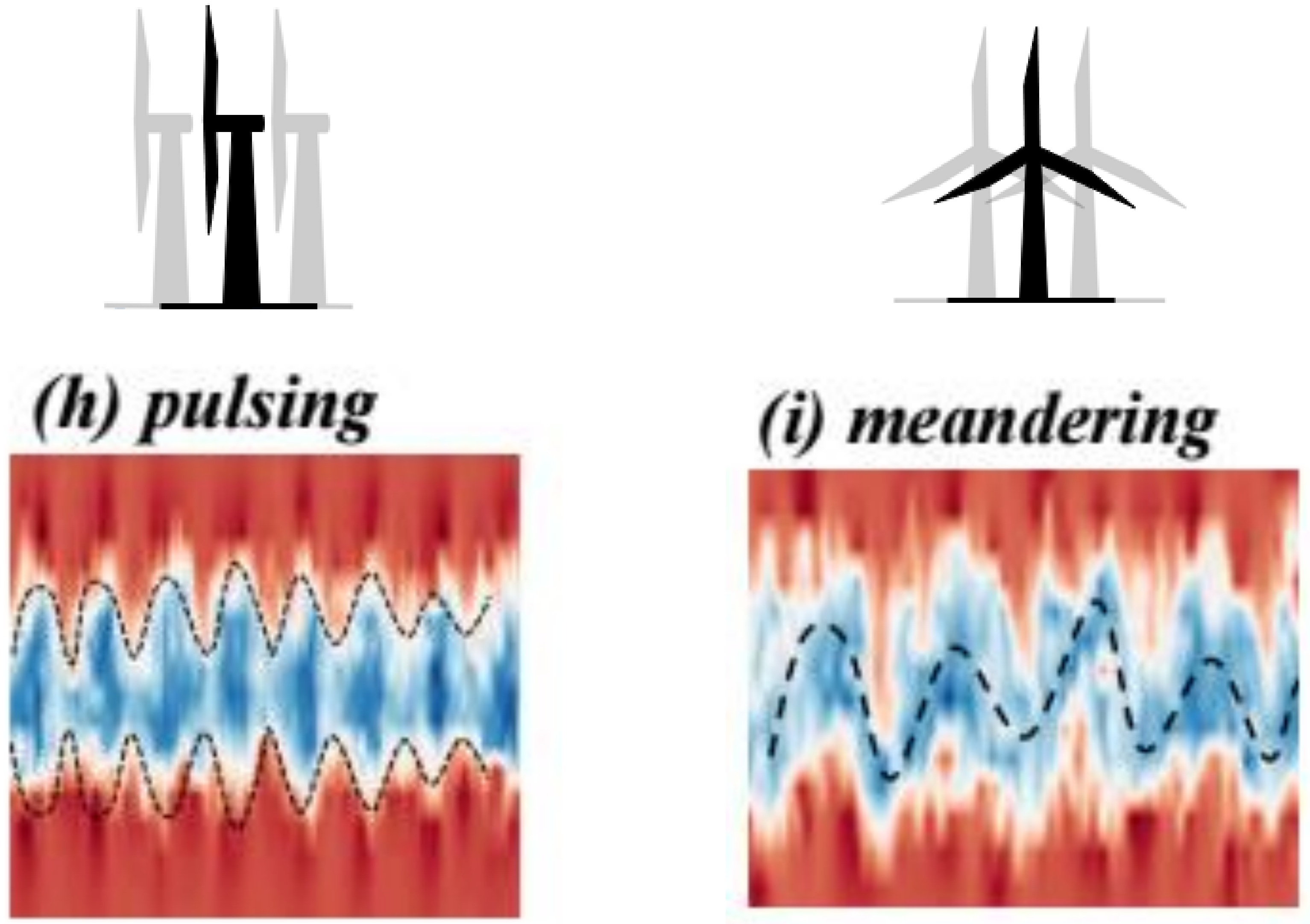
Wake recovery balance (Milan, $TI_\infty \approx 1.5$ %)



- Region of large variations: X/D in [3D, 7D]
- Exch. of momentum driven by ∇ of turbulent fluctuations (Reynolds stresses), $(\partial_y < v'u' >)/U$ and), $(\partial_z < u'w' >)/U$
- Floating's turbine's movements induce more wind speed fluctuations (small scale turbulence & coherent structures)

Conclusion

- Recovery up to 20% higher with motions in laminar ($TI_\infty \approx 0.3\%$) wind compared to 7% with turbulence ($TI_\infty \approx 1.5\%$)
- Motions accelerate transition to far-wake and enhance intensity of recovery
- Induce larger wind speed fluctuations (Reynolds stresses)
- Movements generate coherent flow structures in the wake
- Strong dependency to St but also to A*
- Further investigations needed on transition region and with different turbulent conditions



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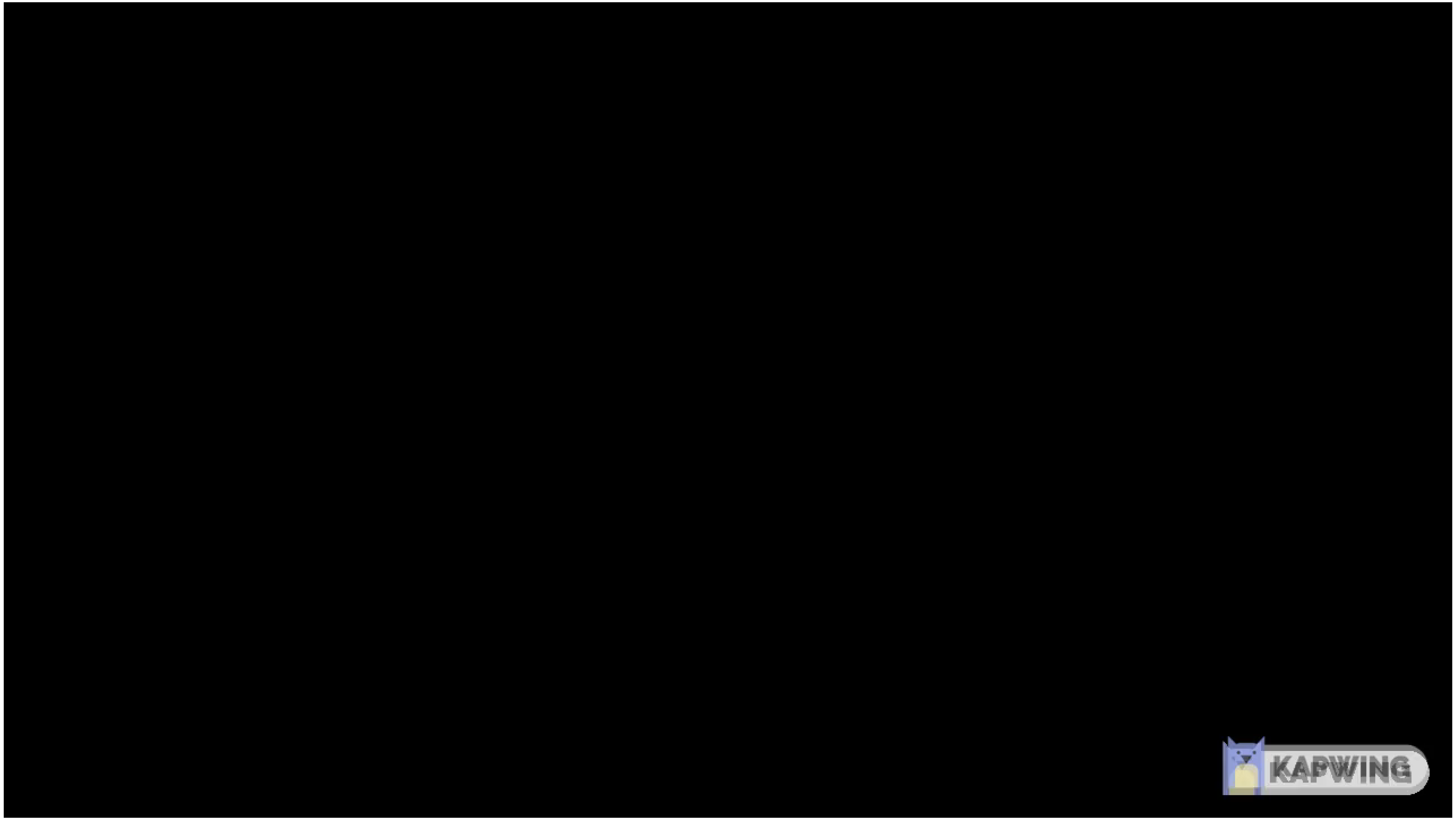
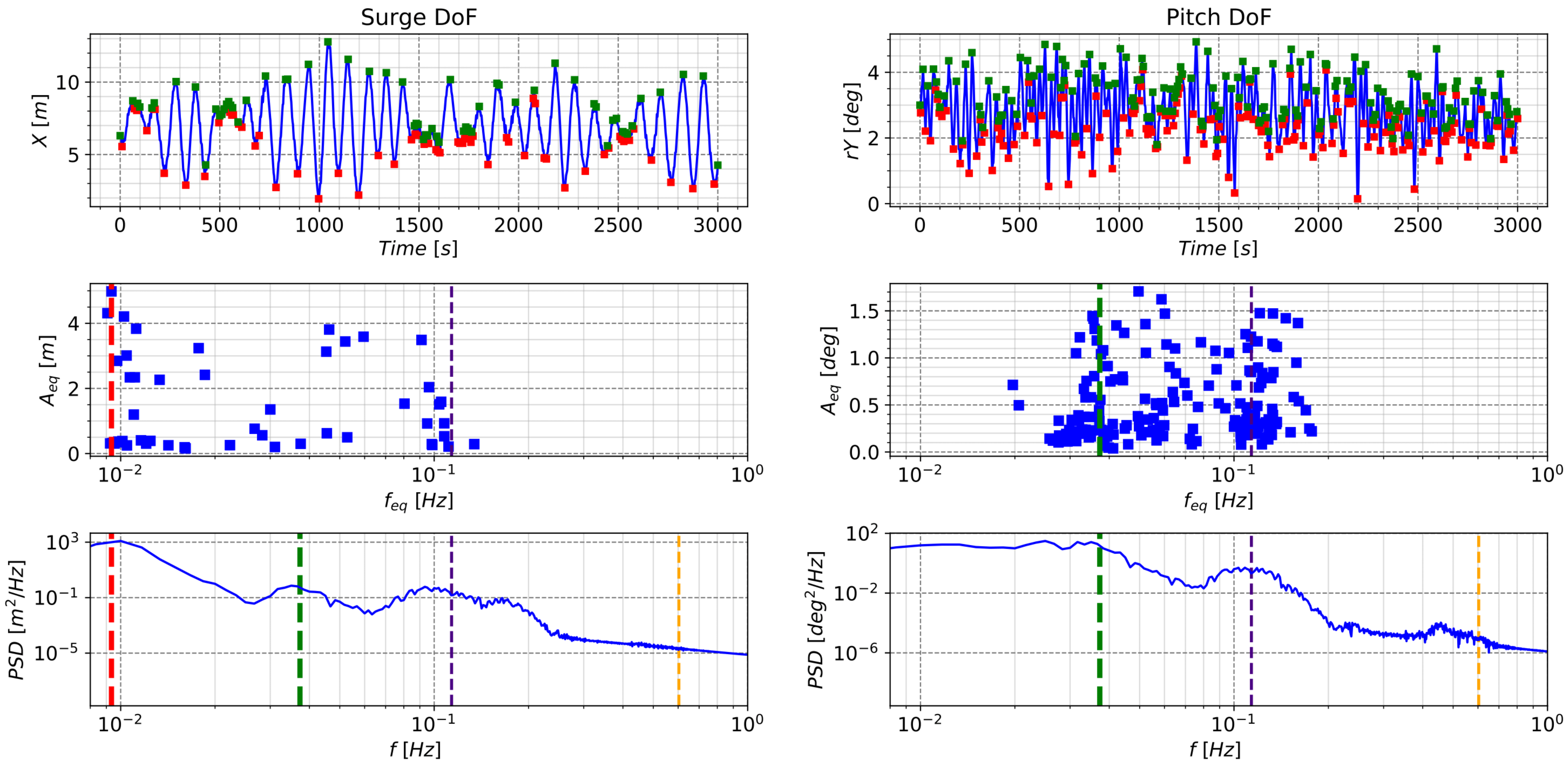


Appendix

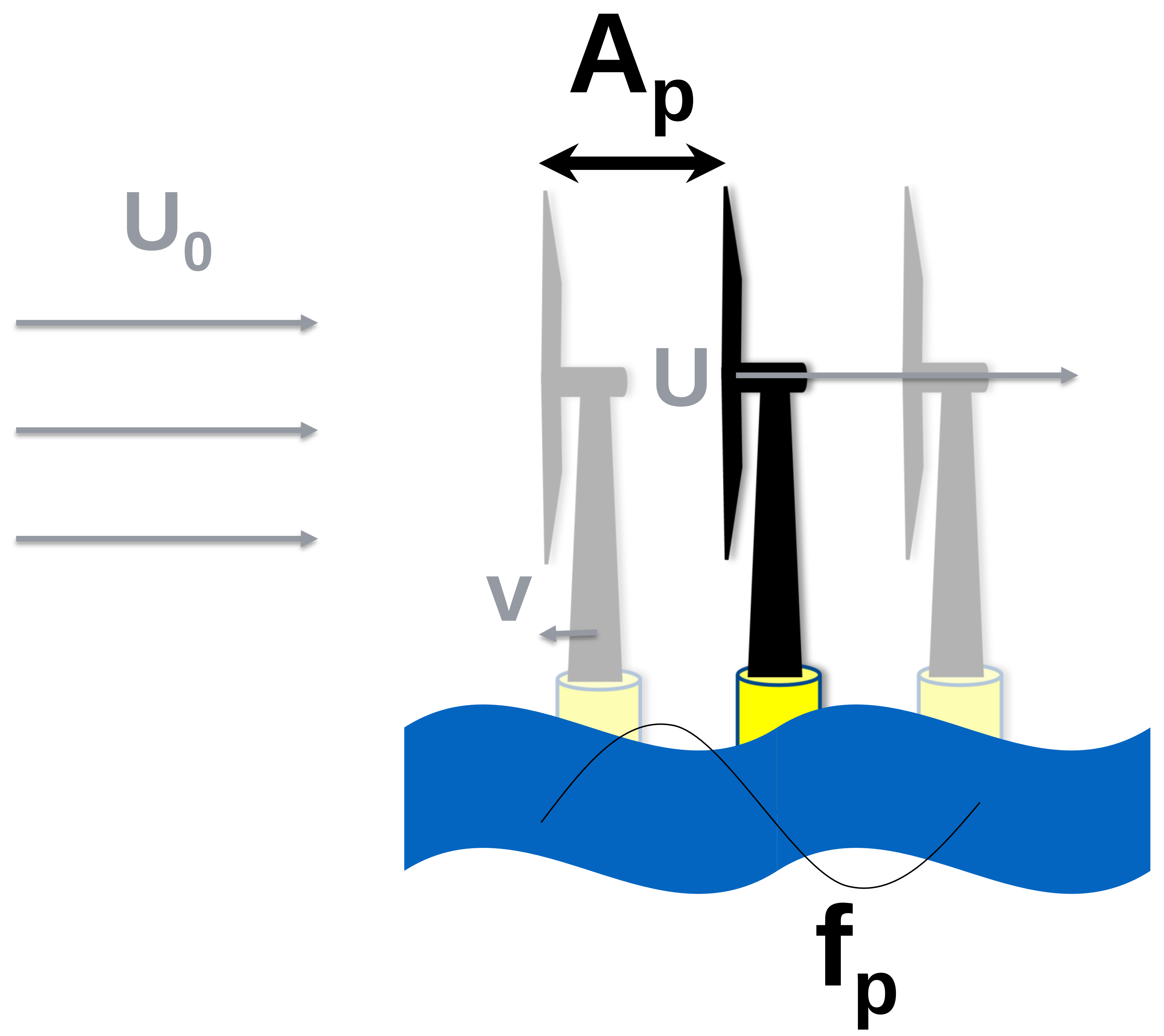
Typical motions of a 5MW FOWT

- **Results from openFAST simulations**
  - 3 floaters (OC4 Semi-sub, Spar, TLP)
  - H_s,T_p in ([1,6] m, [6,10] s)
  - Turbulent wind (U in [5,15] m/s)
- **Analysis of motions show**
  - Motions at floater's natural frequencies, up to 15 m of amplitude
  - Motions at wave's frequencies
  - Motions also driven by large turbulent eddies



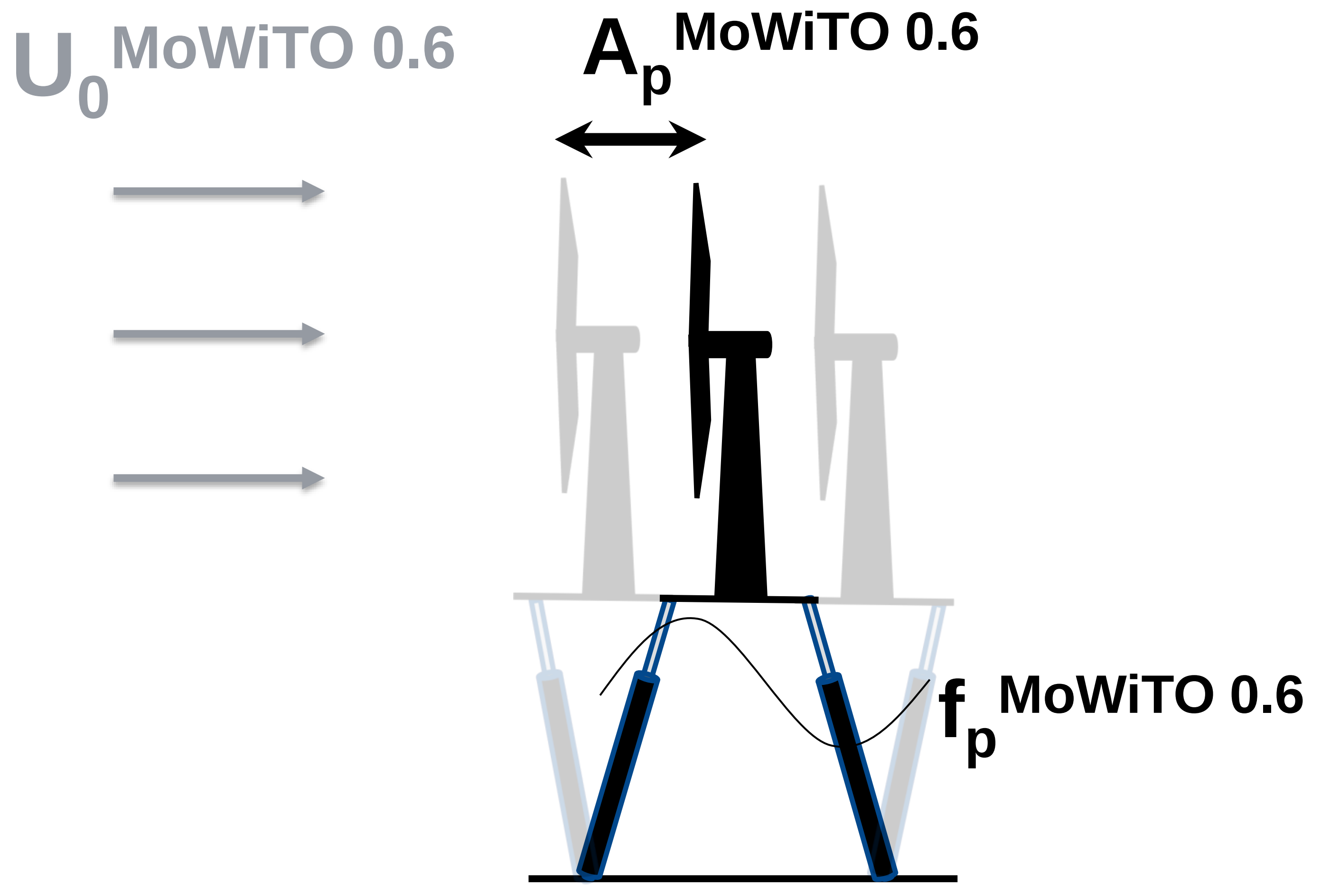
OC4 DeepCwind semi-sub (H_s = 2.1 m, T_p = 8.8 s, U_0 = 13 m/s) simulated with openFAST

NREL 5MW FOWT → MoWiTO 0.6 FOWT



- $\lambda_L = 217$
- $\lambda_V = 1.5$
- $\lambda_T = 145$

- $A_p^{MoWiTO\ 0.6} = A_p^{5MW} / \lambda_L$
- $f_p^{MoWiTO\ 0.6} = \lambda_T \times f_p^{5MW}$
- $U_0^{MoWiTO\ 0.6} = (\lambda_T / \lambda_L) \times U_0^{5MW}$



$\xi(t) = A_p.\sin(2\pi f_p.t)$

$v(t) = d\xi(t)/dt = 2\pi\ f_p\ A_p.\sin(2\pi f_p.t)$

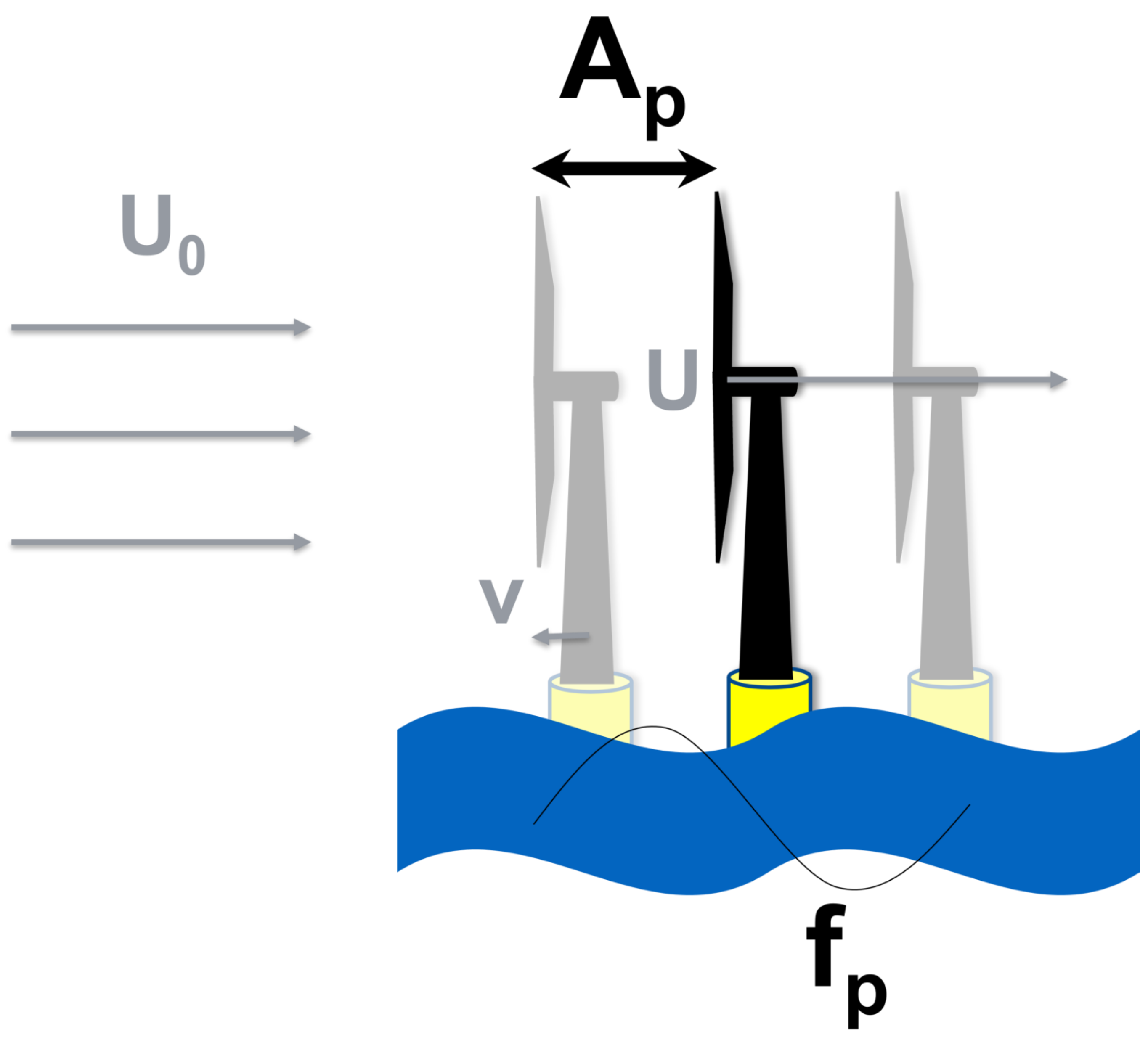
$U(t) = U_0 + v(t)$

Conserve among others

- $f_{red} = f_p \times D / U_0 = (D/U_0) / (1/f_p)$
- ΔC_p
- ΔC_T

Conservation of ΔC_p

- $A_p^{MoWiTO\ 0.6} = A_p^{5MW} / \lambda_L$
- $f_p^{MoWiTO\ 0.6} = \lambda_T \times f_p^{5MW}$
- $U_0^{MoWiTO\ 0.6} = (\lambda_T / \lambda_L) \times U_0^{5MW}$



$\xi(t) = A_p.\sin(2\pi f_p.t)$

$v(t) = d\xi(t)/dt$
$= 2\pi\ f_p\ A_p.\sin(2\pi f_p.t)$

$U(t) = U_0 + v(t)$

Power produced by a WT and power variation due to motion

$P(U, \lambda) = 0.5\ \rho\ \pi\ R^2\ U^3\ C_p\ (\lambda)$ & $\Delta P = P(U_0 + v, \lambda_0 + \lambda_x) - P(U_0, \lambda_0)$

1st order Taylor development

$P(U_0 + v, \lambda_0 + \lambda_x) = P(U_0, \lambda_0) + dP/dU(U_0,\lambda_0) \times v + dP/d\lambda(U_0,\lambda_0) \times \lambda_x$

$\Delta P = 0.5\ \rho\ \pi\ R^2\ (3\ U_0^2)\ C_p(\lambda_0)\ v + 0.5\ \rho\ \pi\ R^2\ U_0^3\ dC_p/d\lambda\ \lambda_x$

$||\Delta C_P|| = 3\ C_p\ ||v|| / U_0 = 3\ C_p\ 2\pi\ f_p\ A_p / U_0$

$||\Delta C_P||^{5MW} = 3\ C_p\ 2\pi\ f_p^{5MW}\ A_p^{5MW} / U_0^{5MW}$

$= 3\ C_p\ 2\pi\ (\lambda_T \times f_p^{MoWiTO\ 0.6})\ .\ (A_p^{MoWiTO\ 0.6} / \lambda_L) / ((\lambda_T / \lambda_L) \times U_0^{MoWiTO\ 0.6})$

$= ||\Delta C_P||^{MoWiTO\ 0.6}$