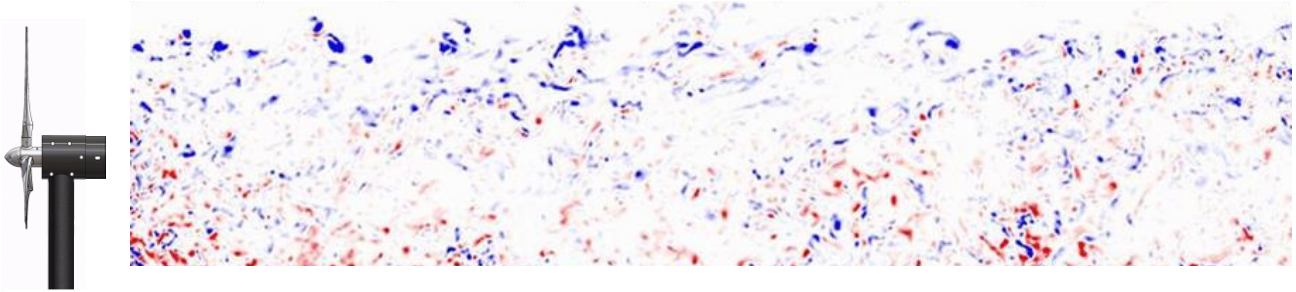

Multiscale energy transfers in the near wake of a model wind turbine

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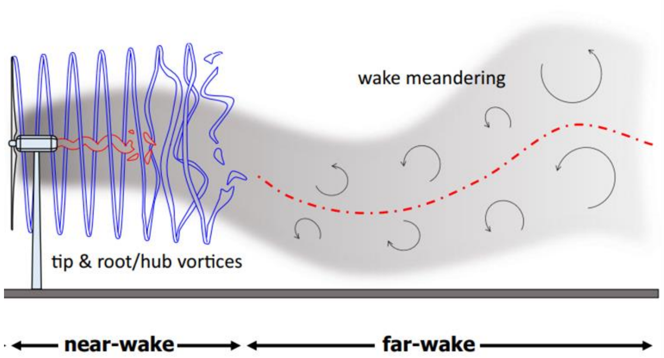
Supervisor – Prof. Oliver Buxton

Multiscale interactions in wind turbine wakes

- Multiscale flows are common in nature and industrial applications
- In multiscale flows coherence is shed at **different length and time scales** simultaneously
- Multiscale flows can be fundamentally different from flows where only one scale is present
    - ➢ Generation of **new coherent structures** [1, 2]
    - ➢ Enhanced mixing [3]

A cityscape

A forest



Wind Turbine wake [4]

[1] **Biswas, N.**, Cicolin, M. M., & Buxton, O. R. 2022, *Journal of Fluid Mechanics*, *941*, A36.
[2] Baj, P. and Buxton, O.R., 2017, *Physical Review Fluids*, *2*(11), p.114607.
[3] Baj, P. and Buxton, O. R. H. (2019), *Journal of Fluid Mechanics*. 864, pp. 181–220.
[4] Porté-Agel, F., Bastankhah, M., & Shamsoddin, S. (2020). *Boundary-layer meteorology*, *174*(1), 1-59.

Important frequencies in wind turbine wakes

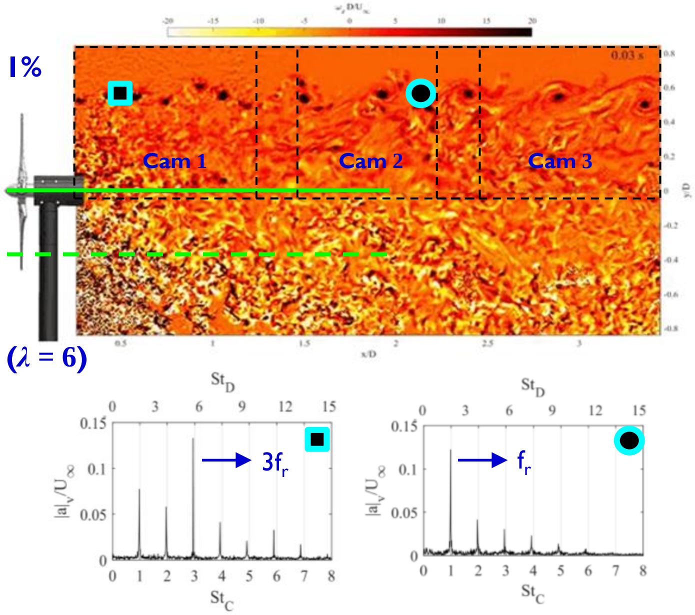
Details in [5]

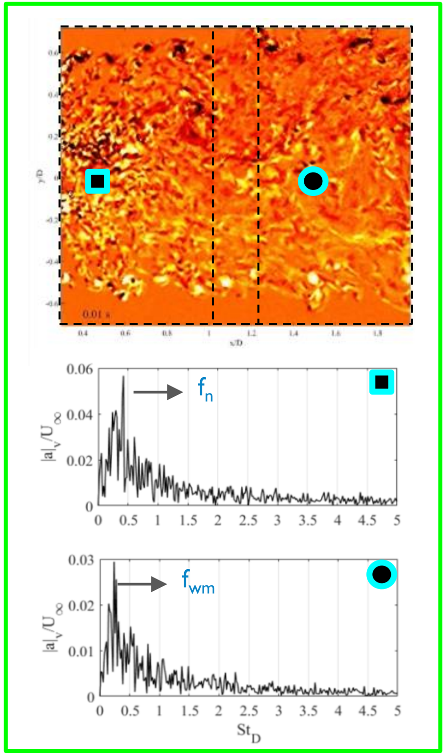
Tip speed ratio $\lambda = \frac{\omega R}{U_\infty}$

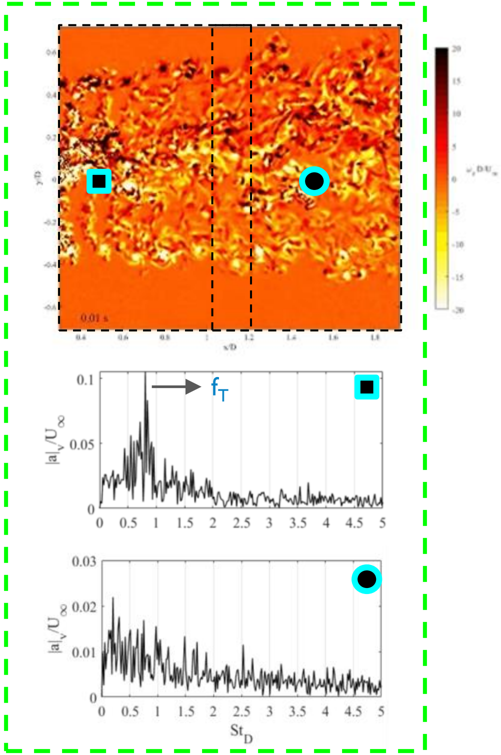
- ω → Rotational speed
- R → Turbine radius
- U_∞ → Freestream velocity

Ti ~ 1%

(λ = 6)



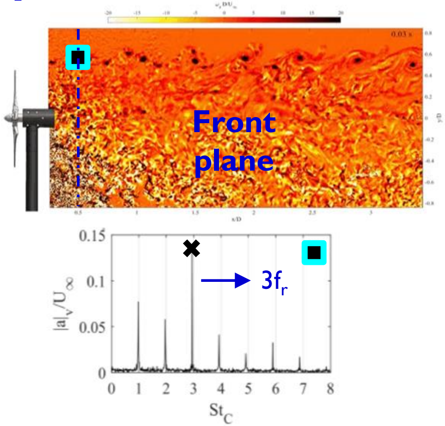




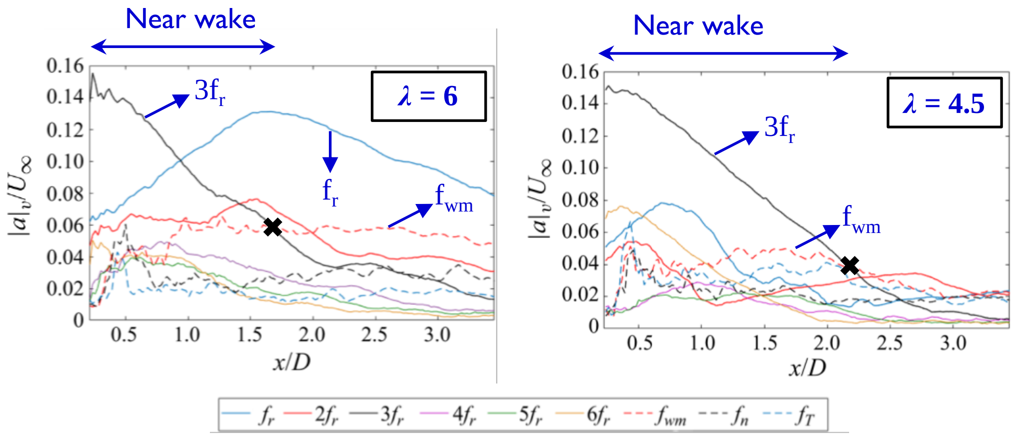
[5] **Biswas, N.** and Buxton, O.R., 2024. *Journal of Fluid Mechanics*, *979*, p.A34.
[6] Okulov, V. L., Naumov, I. V., Mikkelsen, R. F., Kabardin, I. K., & Sørensen, J. N. (2014)., *Journal of Fluid Mechanics*, *747*, 369-380.

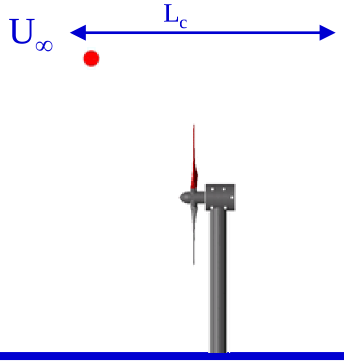
A new definition of the near wake

Details in [5]

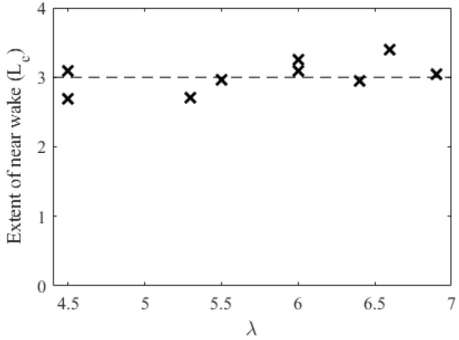


1D





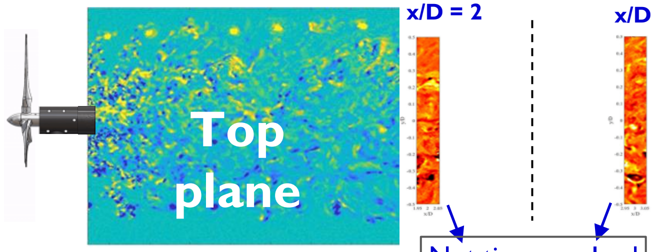
$L_c = 2\pi R/\lambda$



[5] **Biswas, N.** and Buxton, O.R., 2024. *Journal of Fluid Mechanics*, *979*, p.A34.

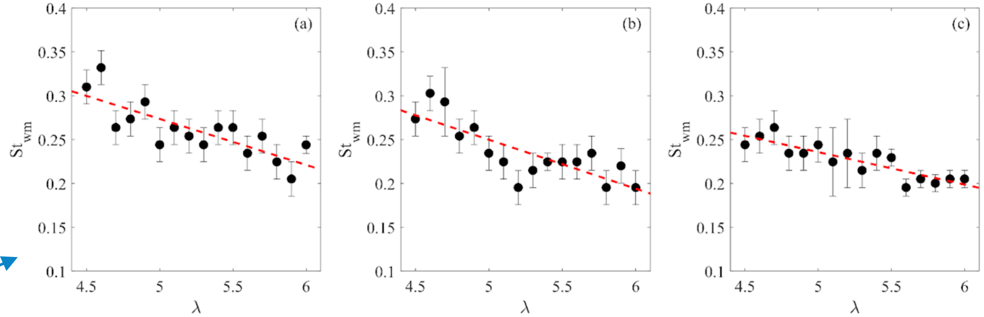
Wake meandering frequency

Details in [5]

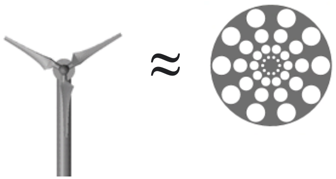


Not time resolved
(long time series)

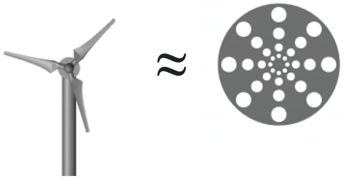
x/D = 2 x/D = 3 x/D = 5

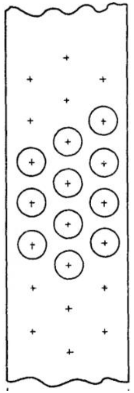


Low **λ** - high porosity



High **λ** - low porosity





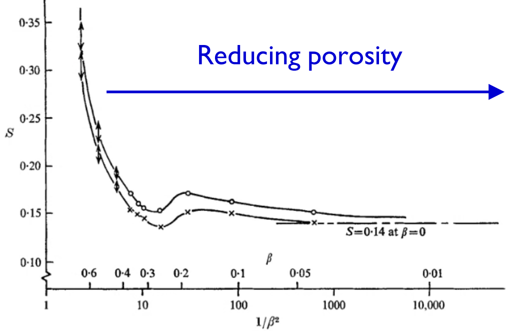


FIGURE 3. Strouhal number *vs.* $1/\beta^2$. —○—, $Re = 2{\cdot}5 \times 10^4$; —×—, $Re = 9{\cdot}0 \times 10^4$; ↕, band of S values.

From [7]

[5] **Biswas, N.** and Buxton, O.R., 2024. *Journal of Fluid Mechanics*, *979*, p.A34.
[7] Castro, I.P., 1971., *Journal of Fluid Mechanics*, *46*(3), pp.599-609.

Mode decomposition (without FST)

Details in [8]

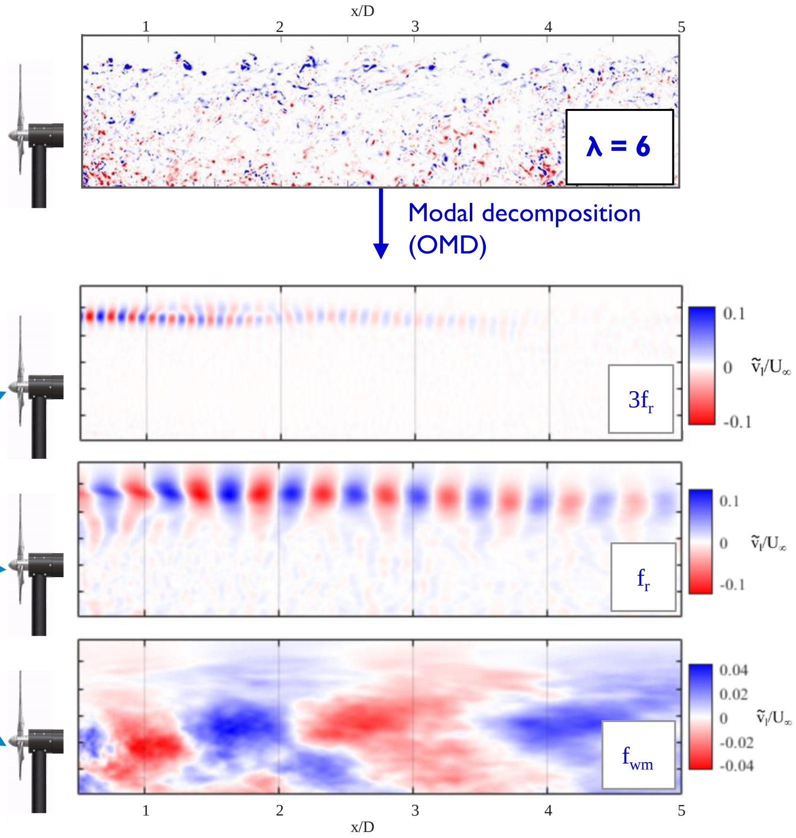
Triple decomposition of velocity field using OMD

$$u(x,y,t) = \bar{u}(x,y) + \sum_{l} \tilde{u}_l(x,y,t) + u^{'}(x,y,t)$$

Mean

Stochastic component

Coherent modes



[8] **Biswas, N.** and Buxton, O.R., 2024. *Journal of Fluid Mechanics*, *996*, p.A8.

Coherent energy budgets

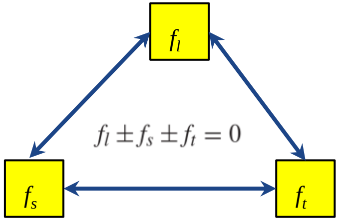
Coherent kinetic energy budget equation, details in [1,2]

$$\frac{\partial \tilde{k}_l}{\partial t} = -\tilde{C}_l + \tilde{P}_l - \hat{P}_l + \left(\tilde{T}_l^+ - \tilde{T}_l^-\right) - \tilde{\varepsilon}_l + \tilde{D}_l$$

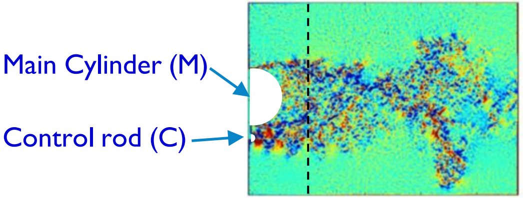
- $\tilde{C}_l$: Convection
- $\tilde{P}_l$: Coherent KE Production (from mean flow)
- $\hat{P}_l$: Stochastic KE production
- $\left(\tilde{T}_l^+ - \tilde{T}_l^-\right)$: Triadic energy Production
- $\tilde{\varepsilon}_l$: Dissipation
- $\tilde{D}_l$: Diffusion

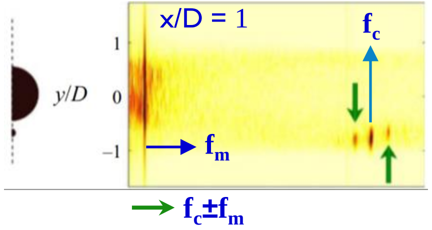
$$\tilde{T}_l^+ = -\frac{1}{2}\sum_{f_s, f_t} \overline{u_i^{f_l} u_j^{f_t} \frac{\partial u_i^{f_s}}{\partial x_j}}.$$

$$\tilde{T}_l^- = -\frac{1}{2}\sum_{f_s, f_t} \overline{u_i^{f_s} u_j^{f_t} \frac{\partial u_i^{f_l}}{\partial x_j}}.$$



[1] studied coherent energy budgets in a flow containing two unequal cylinders and reported

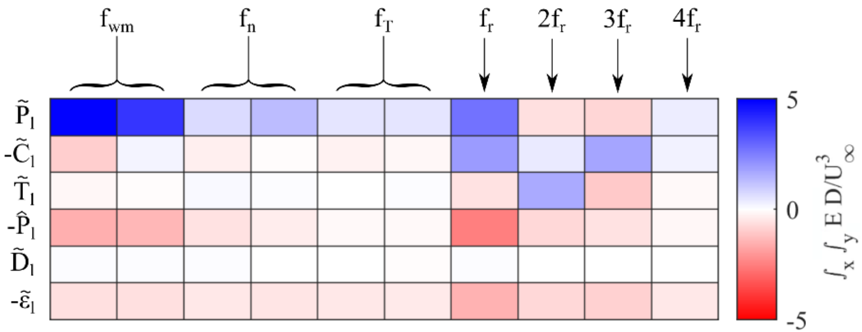




Primary modes: Energised by the mean flow (f_m, f_c)
Secondary modes: Energised by other modes through non-linear triadic interaction ($f_c \pm f_m$)
Mixed mode: Energised by both the mean flow and non-linearity ($2f_m$, $3f_m$)

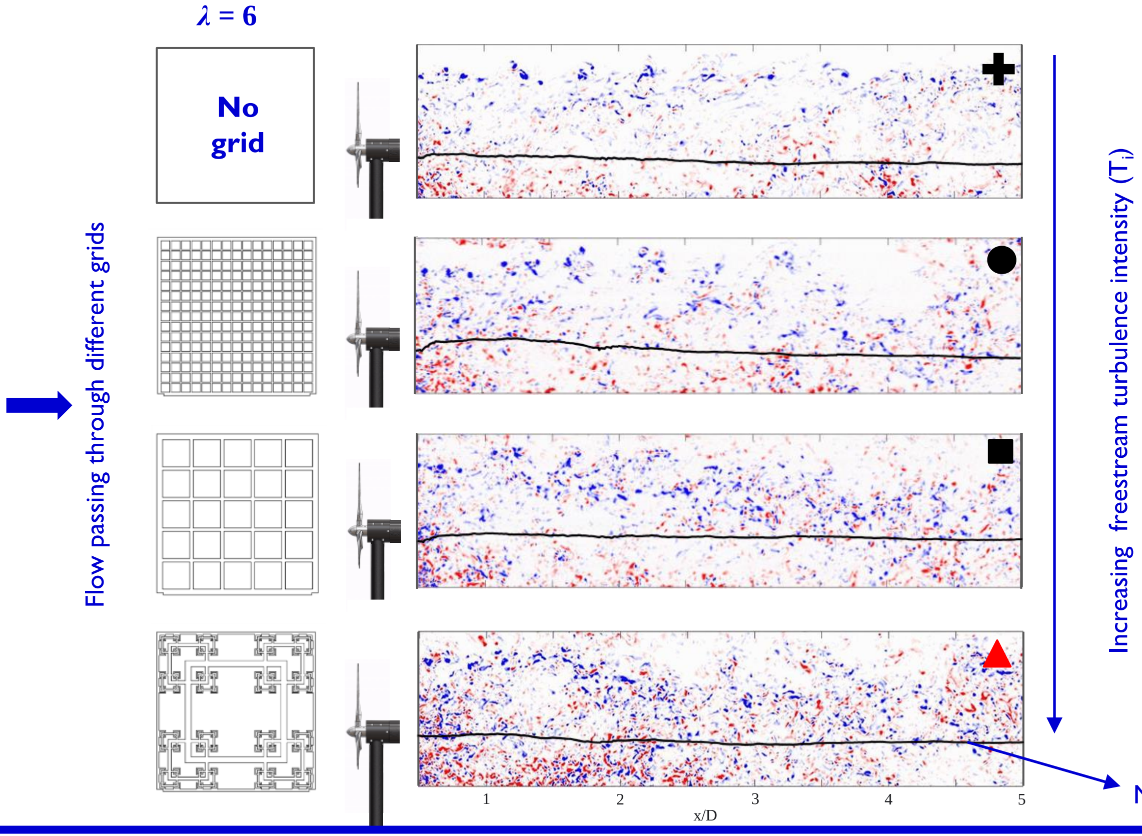
Details in [7]

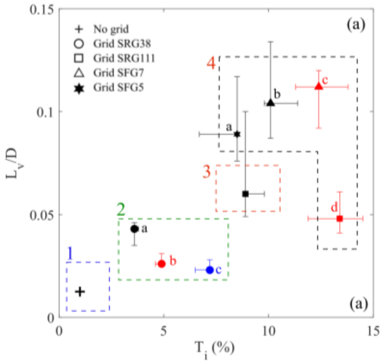
Energy budget terms summed over entire PIV domain ($\lambda = 6$)



[1] **Biswas, N.**, Cicolin, M.M. and Buxton, O.R., 2022. *Journal of Fluid Mechanics*, *941*, p.A36.
[2] Baj, P. and Buxton, O.R., 2017, *Physical Review Fluids*, *2*(11), p.114607.
[8] **Biswas, N.** and Buxton, O.R., 2024. *Journal of Fluid Mechanics*, *996*, p.A8.

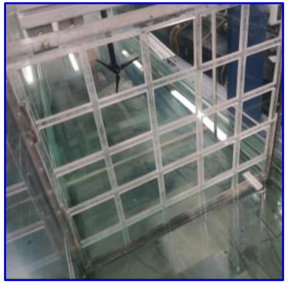
Effect of freestream turbulence (FST)





T_i - Freestream turbulence intensity

L_v - Integral length scales in freestream



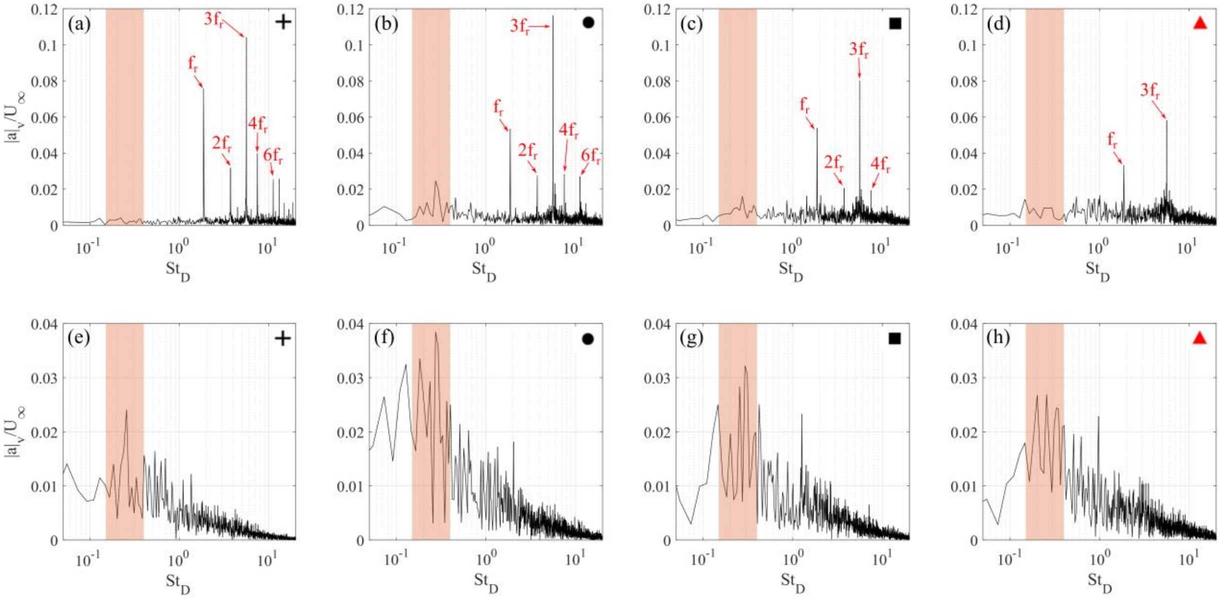
Mean centreline location (y_c)

Important frequencies in presence of FST ($\lambda = 6$)

T_i ~1% | T_i ~3.6% | T_i ~9% | T_i ~12.4%

Tip region, near wake
$x/D = 0.5$, $y/D = 0.55$

Central region, far wake
$x/D = 5$, $y = y_c$



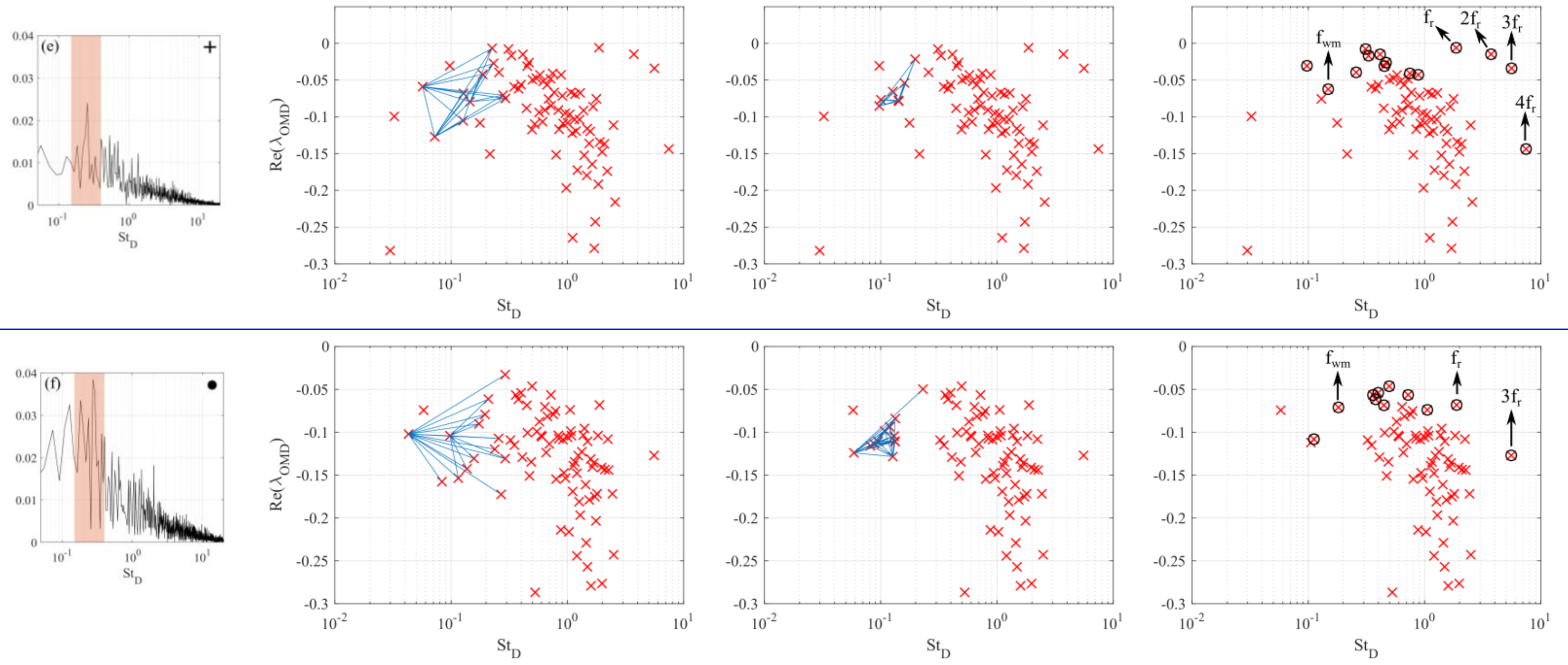
- The tip vortex related frequencies get weaker with increasing FST.
- The energy content in the wake meandering frequency range increases.
- A distinct peak is observed in the wake meandering frequency range for the no grid case.
- Multiple frequencies are present in the wake meandering frequency range in the presence of FST.

Mode clustering for the FST cases

Iteration 1 | Iteration 2 | Iteration 4

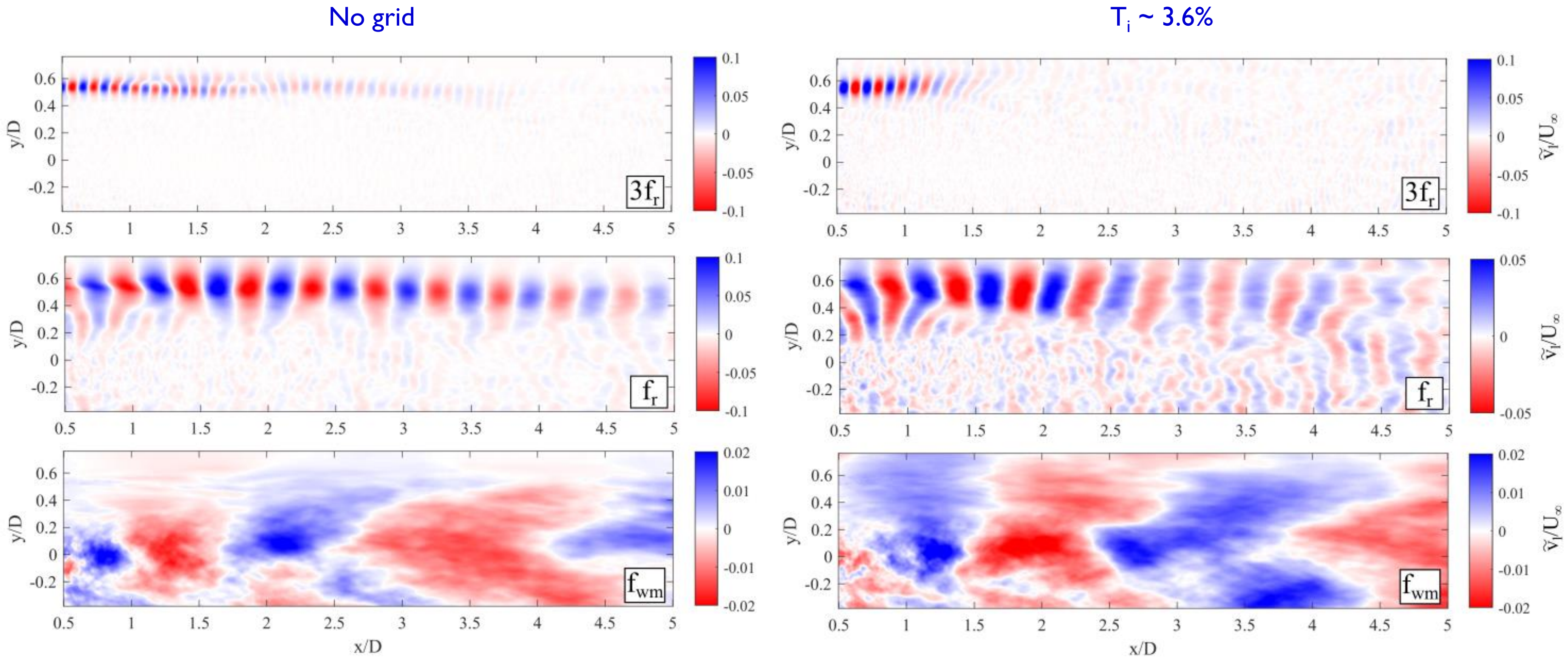
No grid

$T_i \sim 3.6\%$



[9] Beit-Sadi, M., Krol, J. and Wynn, A., 2021. *International Journal of Heat and Fluid Flow, 88*, p.108766.

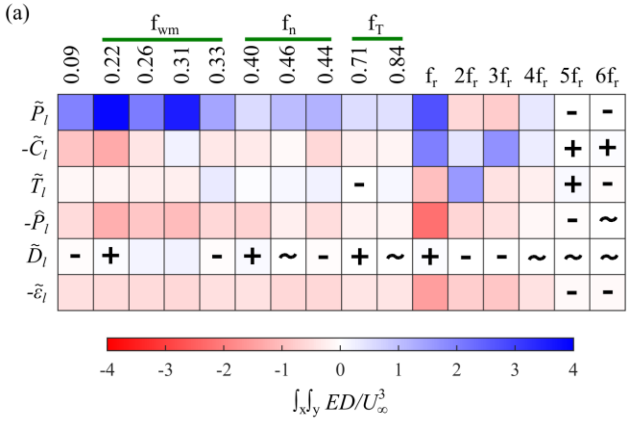
Important modes after clustering



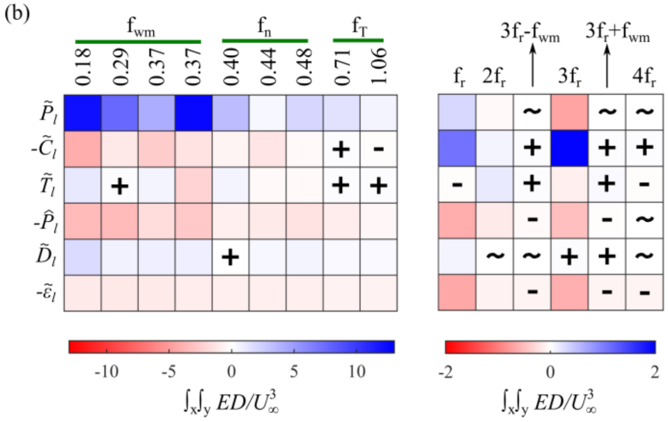
- For the no grid case, the wake meandering mode looks similar before/after clustering (see slide 6).
- Wake meandering mode is stronger and wider in presence of FST.
- The tip vortices breakdown earlier with increasing FST levels.

Energy budget analysis with mode clustering

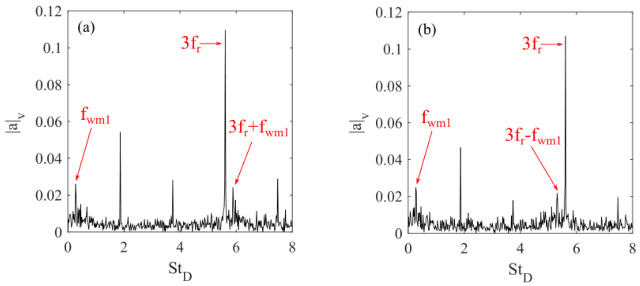
No grid



T_i ~ 3.6%



- For the no grid case, energy budget terms are similar with/without mode clustering.
- With FST, mode clustering does a good job in capturing the physics of the wake meandering modes, *i.e.* the wake meandering modes are stronger with FST. Further, there is a higher contribution from non-linear triadic interaction and diffusion.
- The tip vortices show similar energy budgets but are weaker with FST, triadic interactions are observed between the tip vortices and wake meandering.

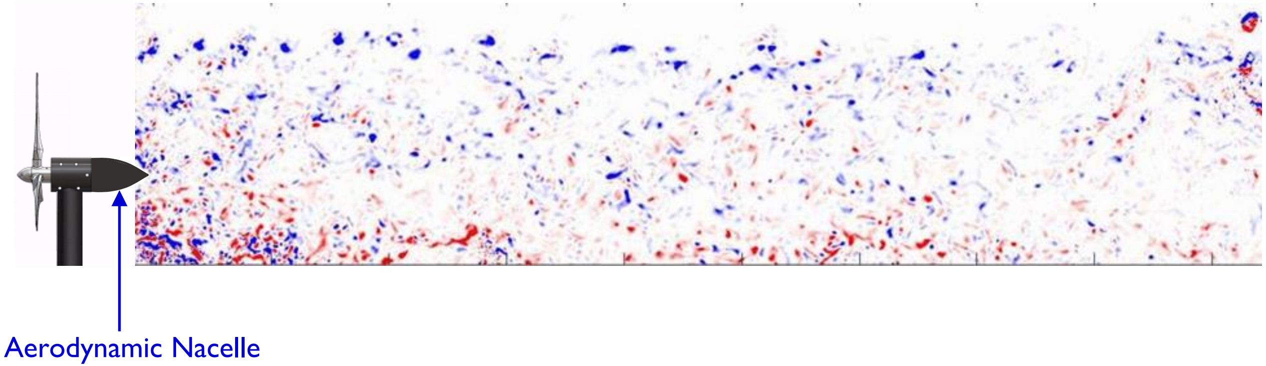


Summary and future work

- We studied the near wake of a model wind turbine using a large number of Particle Image Velocimetry experiments.
- We proposed a new definition of the near wake's extent that is nearly independent of tip speed ratio for low background turbulence.
- We established that wake meandering is related to vortex shedding from the turbine for low background turbulence.
- Freestream turbulence is shown to impact the wake's extent in the same way for different tip speed ratios.

Current and future work will include

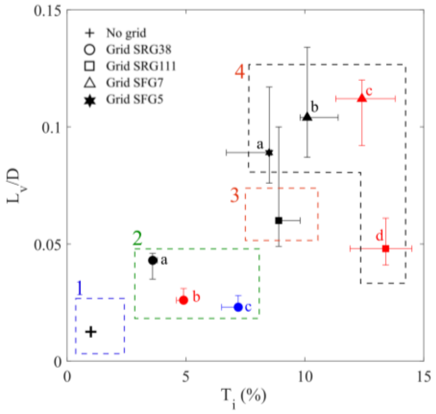
- Understanding the energy exchange processes in presence of background turbulence.
- Understanding the effect of changing the turbine geometry (such as the nacelle or tower shape) on the coherent dynamics.

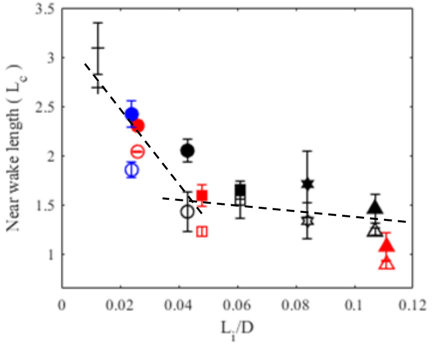


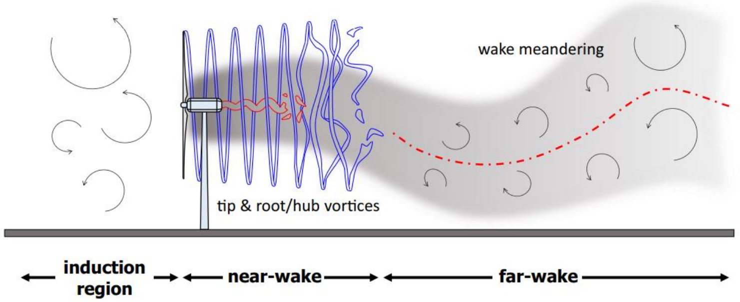
[1] **Biswas, N.**, Cicolin, M.M. and Buxton, O.R., 2022. *Journal of Fluid Mechanics*, *941*, p.A36.
[5] **Biswas, N.** and Buxton, O.R., 2024. *Journal of Fluid Mechanics*, *979*, p.A34.
[8] **Biswas, N.** and Buxton, O.R., 2024. *Journal of Fluid Mechanics*, *996*, p.A8.

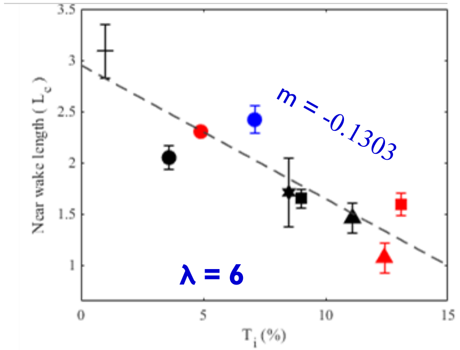
IMPERIAL

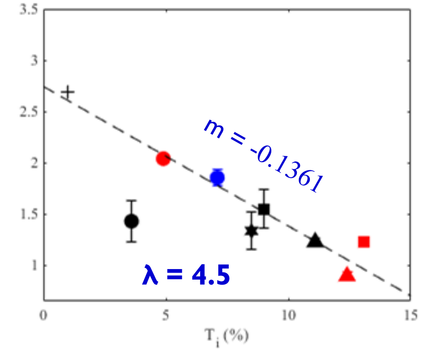
Effect of freestream turbulence on the near wake





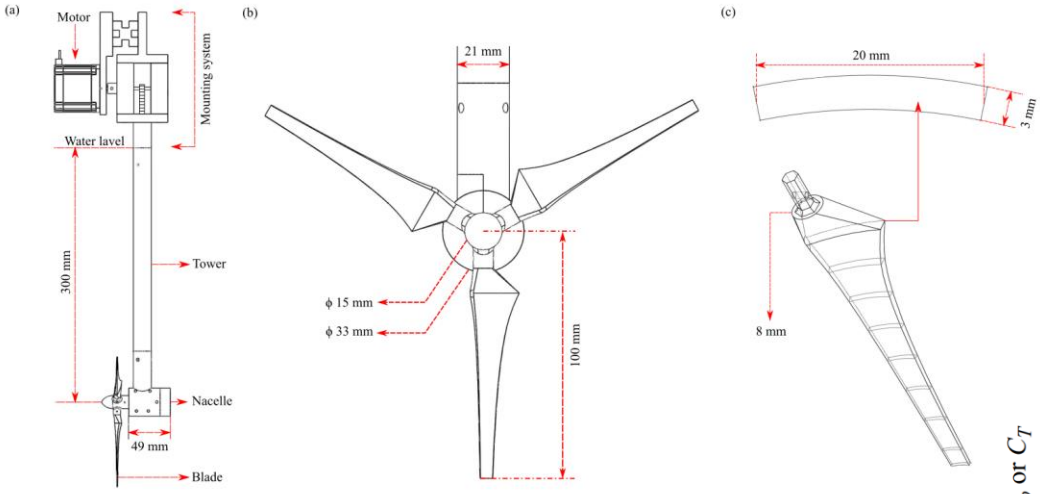


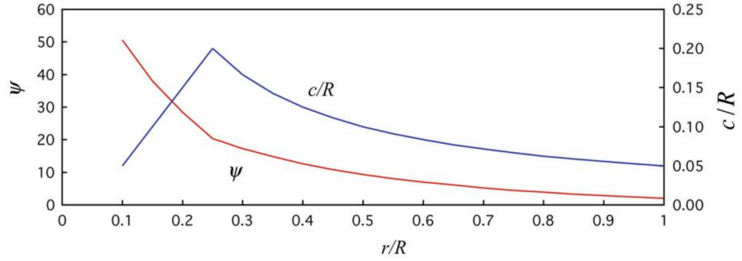




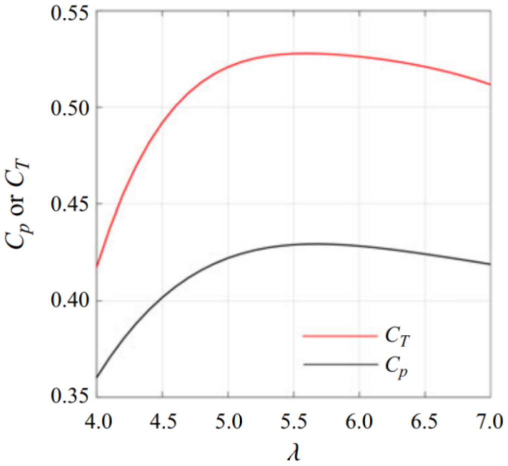
- Near wake length reduces with freestream turbulence intensity
- Large integral length scales likely have minimal impact on wake extent

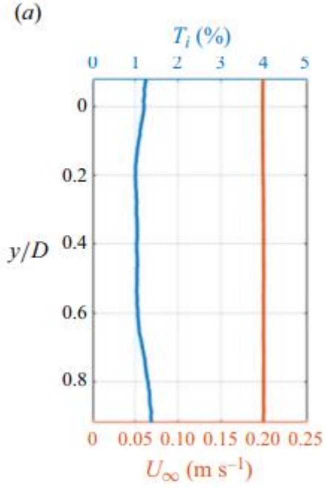
Wind turbine design





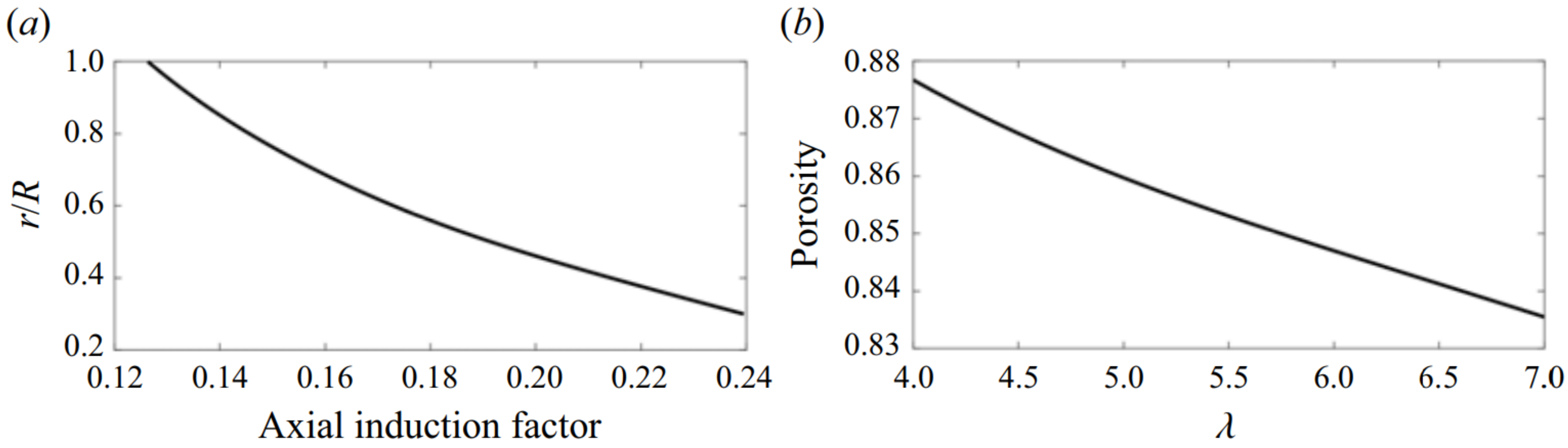
- Freestream velocity = 0.2 m/s
- Max chord based Re ~ 9000
- Flat plate airfoils perform better at low Re [9].



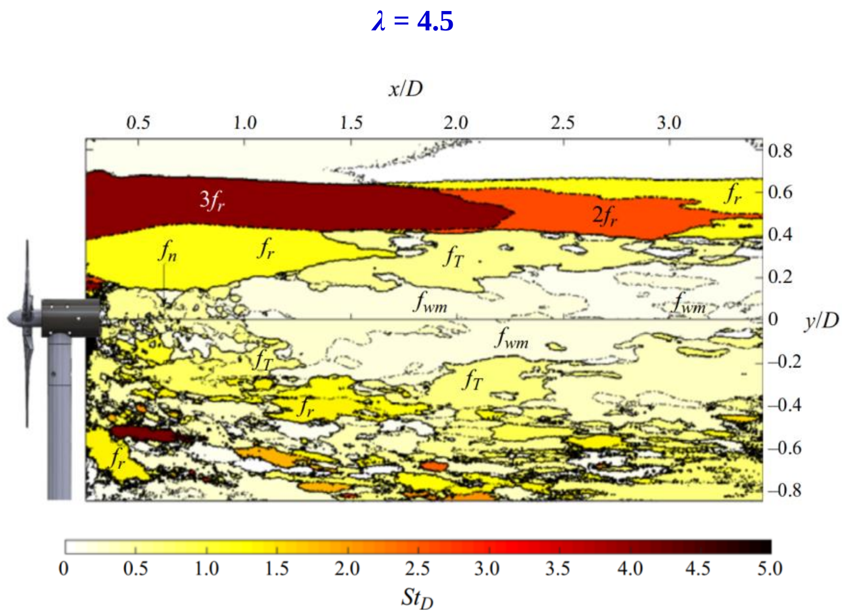


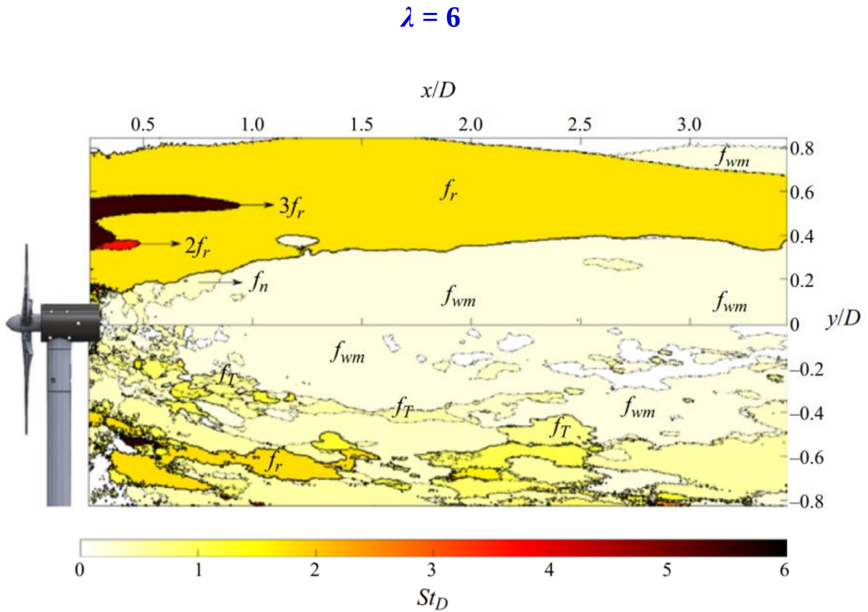
[9] Sunada, S., Sakaguchi, A. and Kawachi, K., 1997. Airfoil section characteristics at a low Reynolds number.

Effective porosity



Dominant frequency maps

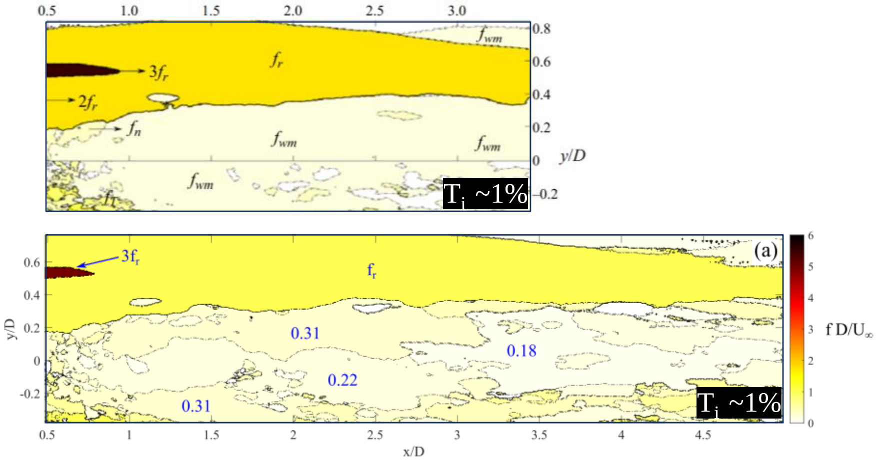


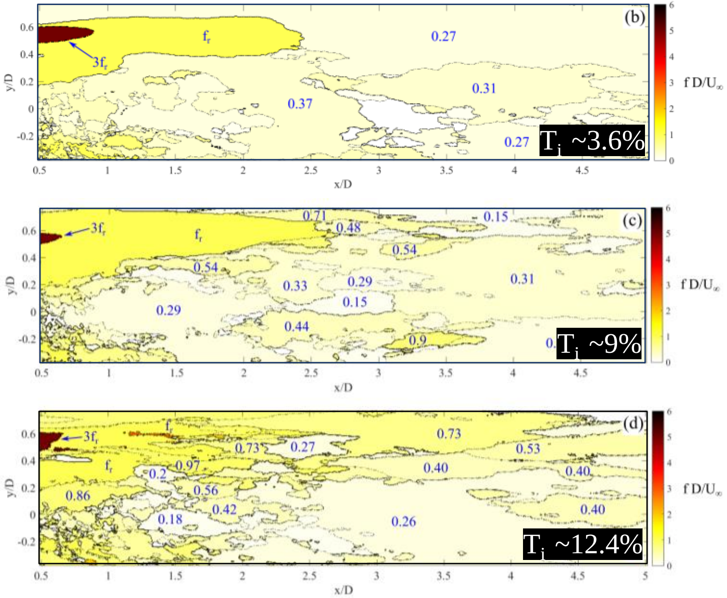


- Tip vortices form a shell-like structure preventing interaction between the core region of the wake and the outer non-turbulent background.
- The core region is dominated by the wake meandering frequency (f_{wm}) which is stronger for higher λ.

[5] **Biswas, N.** and Buxton, O.R., 2024. *Journal of Fluid Mechanics*, *979*, p.A34.

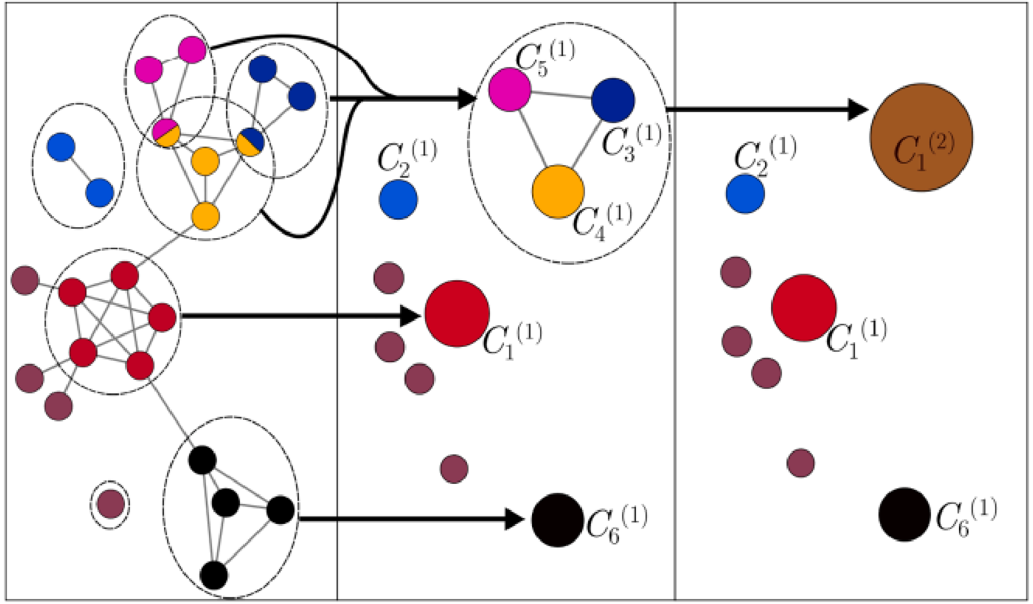
Dominant frequency maps for differebt levels of FST ($\lambda = 6$)





- The shell-like structure breaks down in presence of freestream turbulence.
- More frequencies are excited in the inner wake region, making wake meandering a more broadband phenomenon.

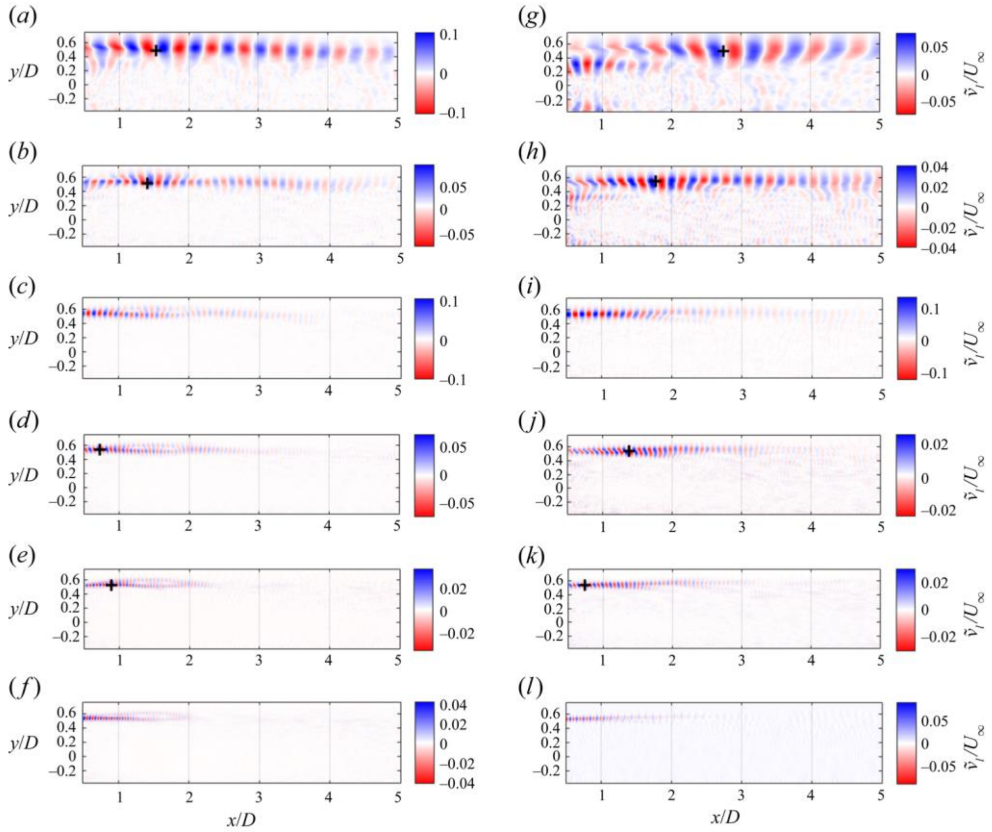
Mode clustering

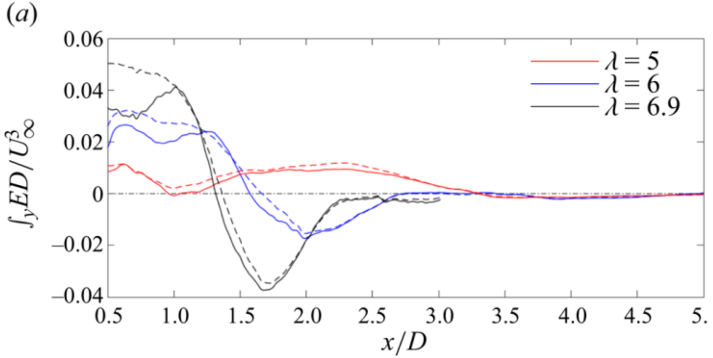


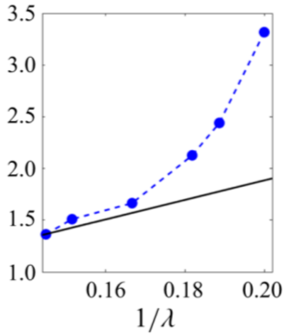
$$UU^\top \mathscr{X} \subseteq \bigcup_{i=1}^{n} \text{span}_{\mathbb{R}}(\text{Re}(\phi_i), \text{Im}(\phi_i)).$$

$$\theta_{ij} = \sin^{-1}\left(\|A_i - A_j(A_i^\top A_j)\|_2\right)$$

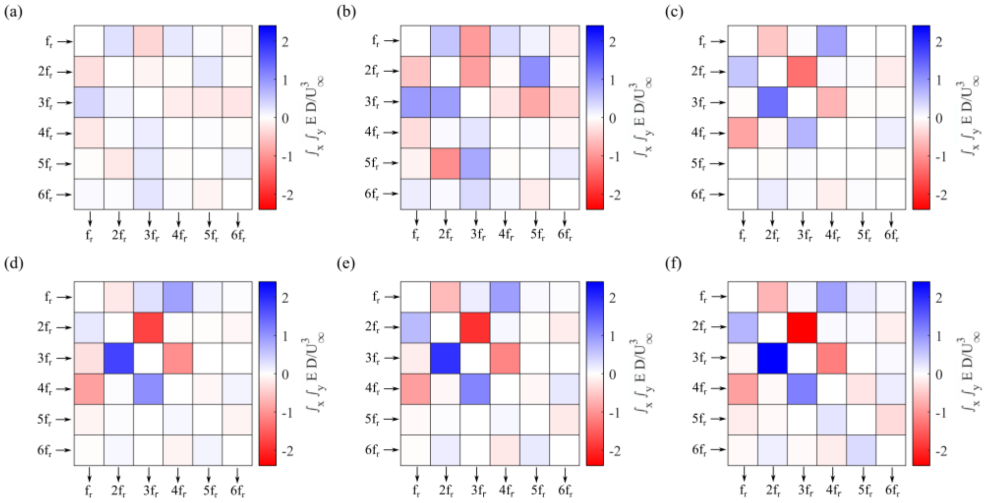
All modes


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
y/D
x/D
$\tilde{v}_l/U_\infty$
0.1
0
−0.1
0.05
−0.05
0.02
−0.02
0.04
−0.04


(a)
$\lambda = 5$
$\lambda = 6$
$\lambda = 6.9$
$\int_y ED/U_\infty^3$
x/D


$1/\lambda$

Triadic interaction



Net traidic transfers for (a) $\lambda = 5$, (b) $\lambda = 5.3$, (c) $\lambda = 5.5$, (d) $\lambda = 6$, (e) $\lambda = 6.6$, (f) $\lambda = 6.9$.