Unravelling the multiscale dynamics in wind turbine wakes

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Summary

Over recent years, the world has seen a tremendous growth in the wind energy sector, with a 4.5 fold increase in the global wind energy production capacity between 2010 and 2021 [1]. However, aligning with ambitious net-zero targets still requires colossal efforts to exploit the full potential of wind energy resources. As a wind turbine extracts energy from the incoming flow, a region is formed behind the turbine that has low momentum and involves complex time dynamics. This region is denoted as the ***wake*** of the turbine. For full scale turbines, this region can extend for kilometers downstream and impact other turbines. Therefore, inside a wind farm, if a turbine is placed in the wake of an upstream turbine, the downstream or so called *'waked'* turbine can produce as much as 50% less power than the upstream machine and is vulnerable to fatigue damages due to time-varying loads [2]. With ever increasing turbine diameter, particularly for offshore turbines, the turbine spacing is no longer a free parameter that can be solely decided based on optimising for total power output, rather land/area related constraints also become a key factor. Therefore, a better understanding of the spatial development of a turbine-wake, as well as its dynamic properties, is necessary. In this work we mainly focus on the latter. We characterise the important frequencies in the wake of a scaled turbine using experiments. We report a series of new physics on how these frequencies are formed and how they interact with each other. Further, we characterise how they depend on the operating condition of the turbine. These physical inferences can easily be translated into industry level applications such as smarter designs of individual components of upstream wind turbines (thereby controlling the shed frequencies) and different designs for the downstream turbines (that face the frequencies).

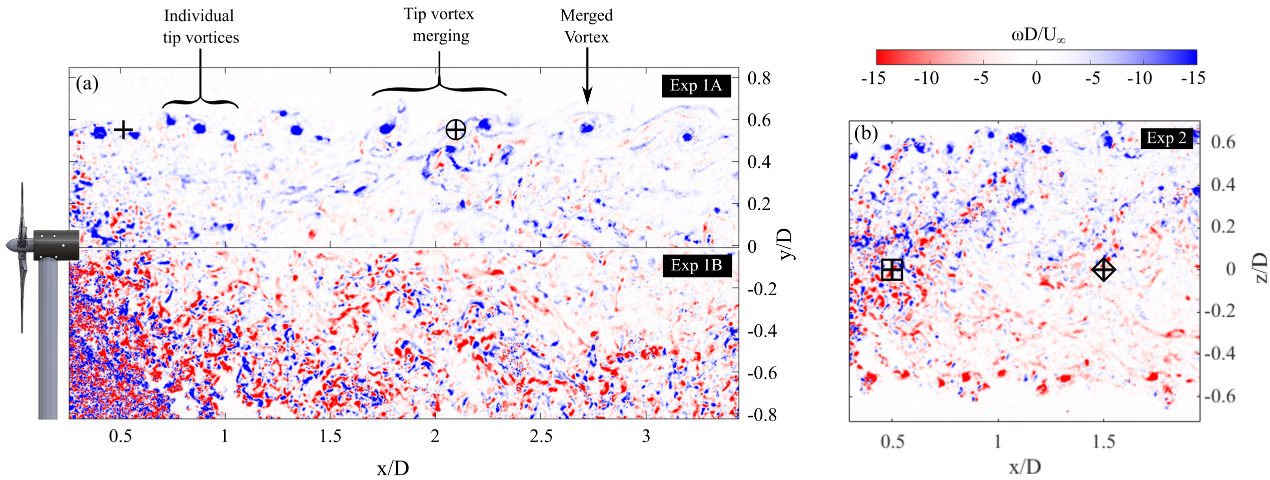

Figure 1: Instantaneous vorticity field of a model wind turbine wake in (a) the $xy(z=0)$ plane and (b) the $xz(y=0)$ plane for $\lambda = 6$.

Objective

The objective of the present work was to understand the multiscale coherent dynamics of the wake of a model wind turbine by obtaining experimental data of unprecedented spatial and temporal accuracy. The importance of the nacelle and tower in the evolution of the turbine's wake has been realised rather recently [3]. Hence, a major focus was to understand the dynamics in the presence of a realistic nacelle and tower. We recently had several breakthroughs in understanding multiscale flows through experiments on simplified two dimensional multiscale flows. One of them being the identification and distinction of ***primary modes*** (energised by the mean flow), ***secondary modes*** (energised by non-linear triadic interactions with other modes) and ***mixed modes*** (with multiple energy sources) [4]. The final goal was to apply the same modal energy budget analysis on a wind turbine wake and answer if similar modes and energy exchange pathways exist in a more complex three dimensional multiscale flow.

Methodology

We conducted extensive Particle Image Velocimetry (PIV) experiments on a small-scale wind turbine consisting of a rotor, nacelle and a tower, mimicking a real-scale wind turbine. We considered a range of tip speed ratios $4.5 \leq \lambda \leq 6.9$

($\lambda = \Omega R/U_\infty$, where R is the turbine radius, Ω is the rotational speed, and U_∞ is the freestream velocity). Fig. 1(a) shows a 'side view' of the instantaneous vorticity field obtained by snapshots from two non-synchronous sub experiments, 'Exp 1A' and 'Exp 1B' for $\lambda = 6$. Each sub experiment used three phantom v641 cameras with overlapping FOVs in cinematographic mode at an acquisition frequency of 100hz, which was significantly higher than the turbine's rotational frequency, $f_r \approx 1.89$hz. Similarly, fig. 1(b) shows a representative 'top-view' of the wake at a central plane. An array of tip vortices can be seen in the tip region ($y \approx +0.5D$) that undergo merging downstream and form larger vortices with a higher pitch (separation). Contrastingly, for $y < 0$ *i.e.* behind the tower, the wake is more turbulent and chaotic due to the interaction between the tip vortices and the tower's vortex shedding. The merging and the breakdown of the tip vortices has been shown to be a necessary step in re-energising the wake which is beneficial for the subsequent turbines [5].

Characterising the frequencies in the wake

By obtaining the frequency spectra at certain points of interest (shown by the free or enclosed + signs in figs. 1(a-b)), we found different dominant frequencies in different parts of the wake (see fig. 2(a)). For instance, near the rotor, at the tip region, the tip vortices (with a characteristic frequency of $3f_r$) dominate, while further downstream, owing to the tip vortex merging process, the dominant frequency changes to the turbine's rotational frequency (f_r). Around the central region ($y \approx 0$ and $z \approx 0$) however, the nacelle's shedding frequency (f_n) dominates near the rotor. Further downstream, the dominant frequency switches to wake meandering (f_{wm}), a term commonly associated with the large scale transverse oscillations of the entire wake [6, 7].

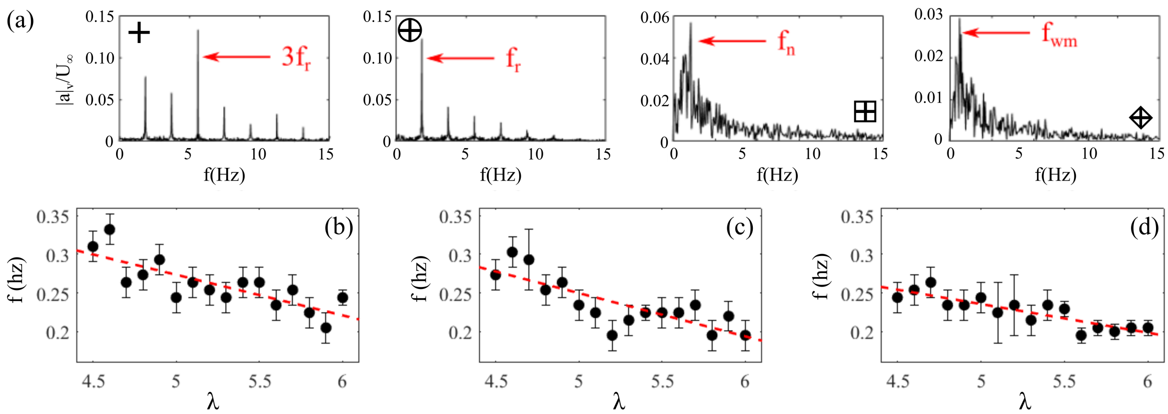

Figure 2: (a) Frequency spectra at the points marked in figs. 1(a-b). Variation of wake meandering frequency with λ at (b) $x/D = 2$, (c) $x/D = 3$, and (d) $x/D = 5$. '- -' shows the linear best fit lines.

Over the years, researchers have held varied opinions regarding the genesis of wake meandering. For example, wake meandering has been seen as large *intermittent* displacements of the entire wake due to passive advection by large scale structures in the incoming flow. On the other hand, even without any inflow turbulence (as in the present case), a *well defined* frequency has been obtained in the wake that has been associated with wake meandering [6], hinting at the possibility of wake meandering being a rotor scale instability or a vortex shedding mode. This to be true, would however require the wake meandering frequency to reduce with increasing λ (which is equivalent to reducing effective porosity), just how the frequency of vortex shedding from a porous plate reduces with reducing porosity [8]. Interestingly, however, [6] reported wake meandering frequency to be independent of operating condition beyond 2.5 rotor diameters. We found that the frequency resolution of the previous studies were not good enough to capture the minute variation of wake meandering frequency with operating condition. Through carefully designed experiments we conclusively showed a decreasing trend of wake meandering frequency with λ at different streamwise locations (see figs. 2(b-d)), ***unambiguously establishing the fact that wake meandering is related to the global vortex shedding mode of the turbine, the frequency of which depends on*** λ. The details of the experiments can be found in our recent work [9].

Energy exchanges and wake recovery

Finally, applying the modal energy budget analysis on the PIV data, ***we showed for the first time that the primary, secondary and mixed modes discovered earlier in two dimensional multiscale flows also exist in a wind turbine wake*** [5]. The modes related to the vortex sheddings from the tower and nacelle as well as wake meandering (shown to be linked to the global vortex shedding mode) were all energised by the mean flow, hence acting like a primary mode. f_r acted as a mixed mode while $3f_r$ (tip vortices) was solely driven by convection in the FOV. Interestingly, $2f_r$ acted as a secondary mode, produced due to non-linear interaction between f_r and $3f_r$. We further quantified the triadic energy transfers to/from different frequencies as shown in fig. 3(a) (the arrows show the direction of energy transfer). The energy transfers are found to be largely concentrated within the first 4 frequencies, thus allowing further simplification. The simplified schematic with the dominant energy transfers are shown in fig. 3(b). Observing the energy transfers in the triad formed by f_r, $2f_r$ and $3f_r$ (shown by the blue arrows), we can say energy is transferred primarily from $3f_r$ to f_r via $2f_r$, indicative of the tip vortex merging process seen earlier. Interestingly, in the other triad formed by f_r, $3f_r$ and $4f_r$, the opposite energy transfer direction is observed, *i.e.* from f_r to $3f_r$ via $4f_r$. ***Such a role of the frequency $4f_r$ has so far been unknown and the balance between these two energy pathways is believed to govern the stability of the tip vortex system. The same pattern of non-linear energy transfers is observed for a range of λs indicating a possible universality*** [5].

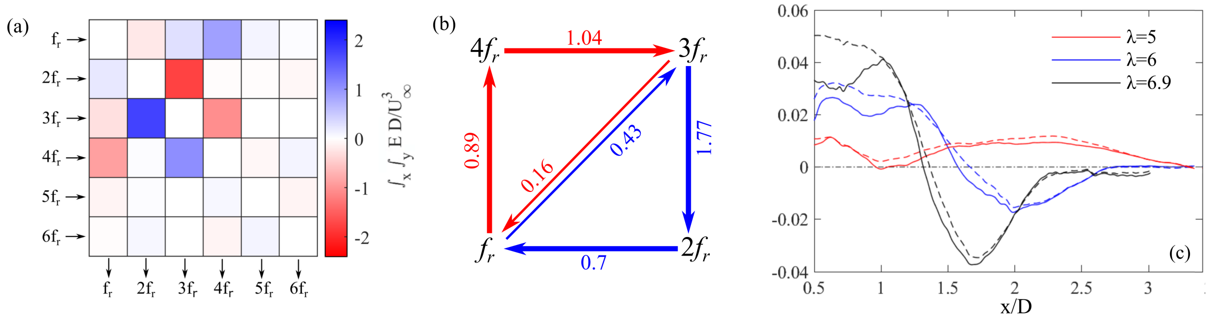

Figure 3: (a) shows the net triadic transfers in the tip vortex system while (b) shows the triad specific dominant energy transfers. (c) shows the streamwise variation of spanwise averaged mean flow production term for the tip vortex system (solid lines) and f_r (dashed line) for diffrerent λs.

From the perspective of wake recovery, the energy exchange between the mean flow and the tip vortex system is critical. In fig. 3(c) we show the variation of spanwise (along y) averaged mean flow production term for the tip vortex system (solid lines) and just for f_r (dashed lines). Note that close to the rotor, the tip vortex system first draws energy from the mean flow as a whole. However, after some distance downstream it starts to transfer the energy back to the mean flow (at least for the higher λs), indicating the initiation of wake recovery. The distance where it happens depends on λ. Further, the energy exchange between the mean flow and the tip vortex system is close to that between the mean flow and f_r alone, especially in the wake recovery region. ***Such an importance of f_r not only indicates the role of tip vortex merging process (that leads to f_r) in wake recovery, but also, it provides us with a simple criterion to mark the streamwise location of initiation of wake recovery***.

List of publications

- **Biswas, N.**, Cicolin, M.M. and Buxton, O.R., 2022. Energy exchanges in the flow past a cylinder with a leeward control rod. ***Journal of Fluid Mechanics, 941***, p.A36.
- **Biswas, N.** and Buxton, O.R., 2023. Multiscale dynamics in turbulent wakes. *Progress in Turbulence X: Proceedings of the iTi Conference in Turbulence 2023 10.*
- **Biswas, N.** and Buxton, O.R., 2024. Effect of tip speed ratio on coherent dynamics in the near wake of a model wind turbine. ***Journal of Fluid Mechanics, 979***, p.A34.
- **Biswas, N.** and Buxton, O.R., 2024. Energy exchanges between coherent modes in the near wake of a rotor model at different tip speed ratios. (Accepted in the ***Journal of Fluid Mechanics***).
- **Biswas, N.** and Buxton, O.R., 2024. Effect of freestream turbulence on the coherent dynamics and energy exchanges in wind turbine wakes (to be submitted to the ***Journal of Fluid Mechanics***).

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