Flapping states of clamped fibres in wall turbulence

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Turbulent boundary layers of natural interest are often perturbed by the presence of slender and flexible obstacles protruding from the bottom surface (e.g., trees in a forest and seaweed on the seafloor). Recent studies[1] have focused on characterising the dynamics of a multitude of such elements (i.e., a canopy[2]) and their interaction with the flow, but the response of an isolated element has not been tackled yet.

This work characterises the dynamical behaviour of a flexible fibre clamped at the wall of a turbulent channel flow (panel *a* of Fig. 1) over a wide set of structural parameters (i.e., the rigidity, the length and the linear density). Our numerical approach solves the Navier-Stokes equations directly, while the fibre is coupled with the fluid through a Lagrangian immersed boundary method and obeys the Euler-Bernoulli equations. We observe two different responses of the fibre to the turbulent flow ($Re_\tau = 180$): it can either resonate at its natural frequency, f_{nat}, or sway at a flapping-frequency dictated by turbulence, f_{turb}. In the former case, attained when $f_{nat}/f_{turb} \gg 1$, the Lagrangian probability density function (PDF) of the spanwise fibre-tip velocity is flattened with respect to the Eulerian PDF of the fluid at a wall-distance equal to the time-averaged wall-distance of the fibre-tip (panel *b* of Fig. 1); the fibre, solicited by the turbulent flow, exhibits an independent response. In the latter scenario, instead, attained when $f_{nat}/f_{turb} \ll 1$, the PDFs of the fibre and of the fluid overlap up to 2σ (panel *c* of Fig. 1); the fibre is therefore fully compliant with the flow.

Our observations are in agreement with the theoretical arguments of Rosti et al.[3] for free fibres in homogeneous isotropic turbulence, thus hinting to a more general behaviour of slender flexible bodies in turbulent flows. Furthermore, the existence of a state where turbulence determines the flapping-frequency suggests the use of submerged flexible fibres for measurements of engineering interest.

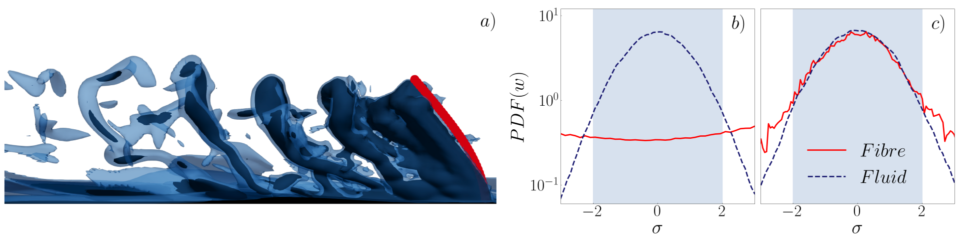

Figure 1: (a) Vortical structures in the turbulent wake of a flexible fibre clamped at the wall, visualised as iso-surfaces of the vorticity magnitude. (b-c) PDFs of the spanwise velocity component (w) of the fibre-tip and of the fluid at the time-averaged wall-distance of the fibre-tip for $f_{nat}/f_{turb} \gg 1$ and $f_{nat}/f_{turb} \ll 1$, respectively. Note that σ is defined, based on the flow velocity, as w/w_{rms}.

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