

Flow structure and loads over inclined cylindrical rodlike particles and fibers

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SUPPLEMENTAL MATERIAL: REGIME MAPS AND CHARACTERISTIC WAKE PATTERNS IN LARGE-REYNOLDS-NUMBER FLOWS PAST INCLINED CYLINDERS

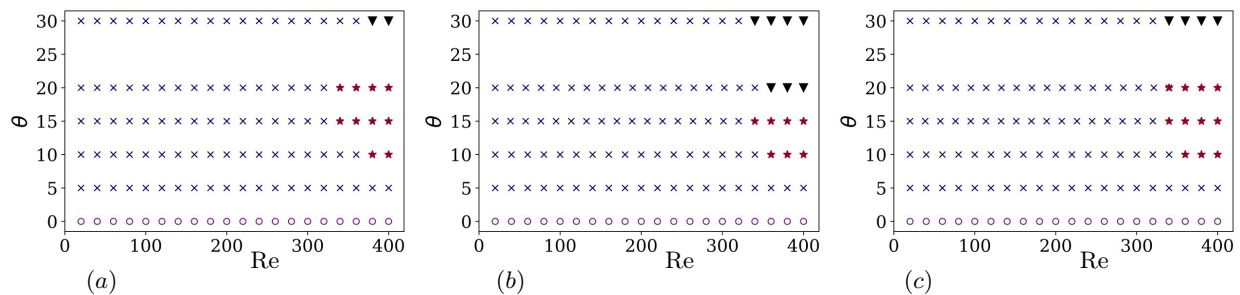


FIG. 1: Wake patterns as a function of θ and Re for (a) $\chi = 3$; (b) $\chi = 5$; (c) $\chi = 7$. Each symbol is associated with a specific wake pattern. \circ : steady toroidal standing eddy; \times : steady pair of counter-rotating streamwise vortices; \star : periodic shedding of double-sided hairpin vortices; \blacktriangledown : shedding of single-sided hairpin vortices.

Figure 1 provides maps of the hydrodynamic regimes observed in the (Re, θ) -plane for inclined cylinders with aspect ratios $\chi = 3, 5$ and 7 . As pointed out in the main text, the wake remains stationary and exhibits a planar symmetry up to a (χ, θ) -dependent critical Reynolds number larger than 300 . To visualize the wake pattern, we make use of the so-called Q -criterion [1], where Q is the difference between the Euclidean norm of the local rotation-rate tensor ω_{ij} and that of the local strain-rate tensor e_{ij} , *i.e.* $Q = \frac{1}{2}(e_{ij}e_{ij} - \omega_{ij}\omega_{ij})$. As Fig. 1 reveals, the steady non-axisymmetric wake regime is the one most frequently encountered in the (Re, θ) -range considered in the present investigation. Figure 2 shows the corresponding wake structure in a typical case: the wake is dominated by a pair of counter-rotating vortices of equal strength, similar to that found in the wake of a sphere just beyond the first bifurcation ($Re \approx 212$).

Unsteadiness arises when the inclination angle is increased beyond $7 - 8^\circ$ and the Reynolds number exceeds a critical value $Re_c(\chi, \theta)$ standing in the range $350 - 380$, depending on χ . For larger inclinations, say $15^\circ \lesssim \theta \lesssim 20^\circ$, Re_c decreases to ≈ 330 , before re-increasing somewhat at larger θ for $\chi = 3$ and 5 . For $Re \geq Re_c$ and $\theta \lesssim 20^\circ$, the wake dynamics is dominated by the shedding of double-sided hairpin vortices which preserve the planar symmetry observed in the previous regime. The hairpins are double-sided because vorticity is shed periodically on both sides of the direction of the main flow, as Fig. 3 exemplifies. The double-sided shedding mode is typical of finite-length cylinders held perpendicular to the incoming flow [2], although in this case the streamwise vortices are shed from the lateral surface, not from the ends as in the present situation. Figure 3(a) also makes it clear that the vortices form at both edges of the cylinder. The shedding is characterized by a single frequency, f , and the Strouhal number $St = fD/U$ is approximately 0.25 for $\chi = 5$.

For larger inclinations and $Re > Re_c$, the wake pattern changes, still preserving a symmetry plane. As Fig. 4 shows, single-sided hairpin vortices all oriented downwards with respect to the direction of the incoming flow are then shed from both ends of the cylinder. The Strouhal number based on the frequency of the dominant shedding mode is slightly less than in the previous regime; *e.g.* $St \approx 0.23$ instead of $St \approx 0.27$ for $\chi = 3$. The single-sided mode observed here is reminiscent of the first unsteady mode in the wake of a fixed sphere, found in the range $272 \lesssim Re \lesssim 350$ [3–6].

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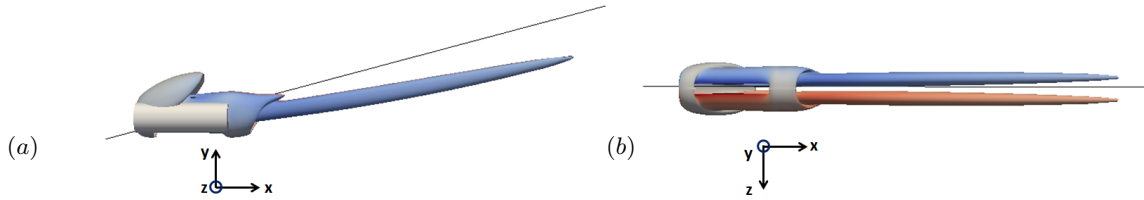


FIG. 2: Wake past an inclined cylinder with $\chi = 3$ at $\theta = 15^\circ$ and $Re = 300$; (a) side view, (b) top view. The two steady counter-rotating vortices are visualized using the $Q = 0.08$ iso-surface colored by the magnitude of the streamwise vorticity (normalized by U/D), ranging from -2 to 2 . The thin line indicates the direction of the upstream flow; the cylinder appears as a grey rectangle on the left of panel (a).

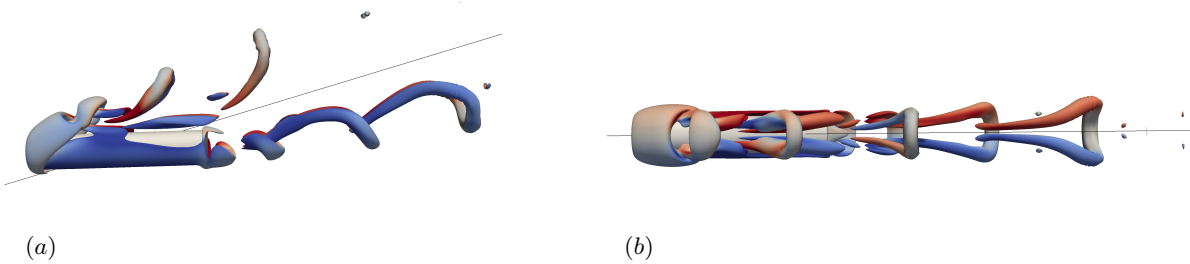


FIG. 3: Wake past an inclined cylinder with $\chi = 5$ at $\theta = 15^\circ$ and $Re = 400$; (a) side view, (b) top view. The double-sided hairpin vortices are visualized with the $Q = 0.25$ iso-surface colored by the magnitude of the normalized streamwise vorticity, ranging from -2 to 2 . The thin line indicates the direction of the upstream flow.

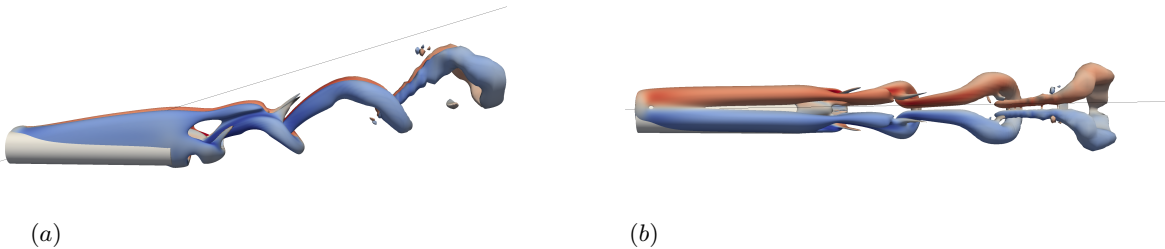


FIG. 4: Wake past an inclined cylinder with $\chi = 5$, $\theta = 20^\circ$ and $Re = 400$; (a) side view, (b) top view. The single-sided hairpin vortices are visualized with the $Q = 0.25$ iso-surface colored by the magnitude of the normalized streamwise vorticity, ranging from -2 to 2 . The thin line indicates the direction of the upstream flow.

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