VORTEX DYNAMICS IN THE TRANSITIONAL AND TURBULENT WAKE OF 6:1 PROLATE SPHEROID AT 45° INCIDENCE ANGLE

Fengjian Jiang[1,2], José P. Gallardo[3] & Helge I. Andersson[1]
[1]*Department of Energy &Processing Engineering, Norwegian University of Science and Technology, Norway*
[2]*School of Naval Architecture & Ocean Engineering, Huazhong University of Science and Technology, China*
[3]*Department of Marine Technology, Norwegian University of Science and Technology, Norway*

Abstract The incompressible flow past a 6:1 prolate spheroid with an inclination angle of 45° at Re = 3,000 has been studied by means of direct numerical simulations (DNS). The Reynolds number is based on the inflow velocity and minor-axis length. The preliminary results presented here are focused mainly on vortex dynamics and vortical structures in the wake. The wake behind this configuration starts almost symmetric but is soon strongly deflected and bent as it evolves to the intermediate wake. A pair of unequal-strength vortices dominates the intermediate wake, of which one exhibits the shape of a long vortex tube while the other rapidly breaks down into turbulent-like vortical structures.

MOTIVATION AND PRESENT APPROACH

The prolate spheroid is a well-defined body of revolution and has been widely used in a variety of engineering fields; for example as a simplified hull-shape of a submarine or unmanned underwater vehicle (UUV), or as a model of a wood fiber in dilute fiber-suspension flows. Among these engineering applications, the aspect ratio 6:1 is most commonly considered. The wake of an inclined prolate spheroid at high incidence angle attracts the interest of researchers in particle suspensions flows, marine hydrodynamics, and aero-dynamics. Nevertheless, published studies at attack angles above 25 degrees are almost non-existing.

When a prolate spheroid is configured at 0° incidence angle, i.e. the major axis aligns with the free stream U_0, the wake remains axisymmetric up to very high Reynolds numbers due to the streamlined body. On the contrary, when the spheroid is configured at 90° incidence, an unsteady laminar wake can be observed at very low Reynolds number of 100, and the symmetry about meridional and equatorial planes breaks successively at Re ≈ 150 and 200 to form hairpin vortices in the wake; El Khoury *et al.* [1]. Different from these two extreme cases, a 45° inclination breaks the axisymmetry and the equatorial planar symmetry of the wake, whereas only a planar symmetry about the meridional plane exists at relatively low Re. Based on our recent DNS study (Jiang *et al.* [2]), the intermediate wake of the 45° angle of attack configuration becomes asymmetric and slightly unsteady at Re = 1,000, while the near-body wake still remains strictly symmetric. A pair of counter-rotating vortices dominates the intermediate wake for all Reynolds numbers considered [2] and it seems that a result of the unequal strength of the two wake vortices accompanies the symmetry-breaking. A similar phenomenon was also observed in the wake of an axisymmetric submarine hull at much lower attack angle (8°) and at a substantially higher Re (of the order 10^6) by Ashok and Smits [3].

The present study focuses on the wake behind the same configuration as in [2], but at the higher Re = 3,000 (based on the minor axis *D* of the 6:1 spheroid), the results of the DNS enable us to study how this complex wake evolves from laminar via transition to turbulence. We use the MGLET-code to solve the 3D incompressible Navier-Stokes equations on a block-structured grid. The grid spacing is uniform in a "central block" which wraps around the spheroid and then gradually stretches outside of this central block. The total number of grid cells amount to 1344×1024×544 (7.49×10^8). A direct-forcing immersed boundary method (IBM) was used to transform the no-slip condition at the spheroid into internal boundary conditions at the nodes of the Cartesian grid.

RESULTS AND DISCUSSIONS

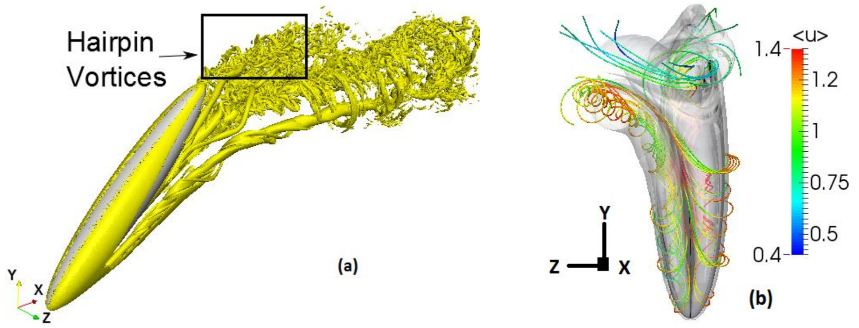

Figure 1. (a) Overview of the wake structures showing iso-surfaces of λ_2= -15; (b) Time-averaged streamlines colored by streamwise mean velocity $\langle u\rangle/U_0$; the iso-surfaces show $\langle\omega_x\rangle D/U_0$ = 1 and -1.

Our previous study at lower Reynolds numbers [2] reported the wake structures behind this configuration, i.e. a pair of symmetric vortex sheets shed from each side of the spheroid dominates the near-body wake, and a pair of streamwise counter-rotating vortex pairs dominates the intermediate wake. At Re = 1,000 the wake appeared to be asymmetric but remained laminar. However, at Re = 3,000 in the present study, the wake becomes by far more complex and no longer laminar. Figure 1(a) provides an overview of the wake at Re = 3,000 using iso-surfaces of λ_2. The structure of the near-body wake remains somewhat coherent which tells us that the wake adopts some of the main structures as at lower Re, but the near-body vortex sheets are no longer symmetric. A strong deflection to an arbitrarily chosen side arises due to a pitchfork bifurcation. One of the vortex tubes develops to a dominating coherent structure in the intermediate wake. Any clues of the existence of a counter-rotating vortex pair cannot be seen in the instantaneous flow field. However, the time-averaged streamlines and iso-surfaces of the time-averaged streamwise vorticity in Figure 1(b) depict the structure of a vortex pair in the downstream wake.
The time-averaged streamwise vorticity distributions show the asymmetric structure of the vortex sheets in the near-body wake in Fig. 2(a) and the unequal-strength of the counter-rotating vortex pair in the intermediate wake can be observed in Fig. 2(b). Spectra analyses of preset probes show two distinct peaks at a main $St_1 = 0.0733$ and a second $St_2 = 2St_1 = 0.15$ all through the wake. It is noteworhty that exactly the same frequencies appear in the frequency analysis of the body forces. It is not yet clear to us from where this main frequency stems since no vortex-shedding-like behaviour can be observed in the three-dimensional wake of the spheroid.
Based on the present observations, we conclude that the near-body wake of a 6:1 prolate spheroid at 45^{o} incidence angle starts almost symmetric but is rapidly deflected to one side and thereafter bent as it evolves to the intermediate wake. The intermediate wake is no longer laminar and the streamwise counter-rotating vortical structures can only be observed in the time-averaged flow fields since the weaker vortex breaks into small turbulent-like vortical structures. In addition, a set of hairpin vortices are observed in the uppermost part of the near-wake. We believe that these horseshoes (see Fig. 1(a)) are a result of a strong instability near the upper pole of the spheroid.

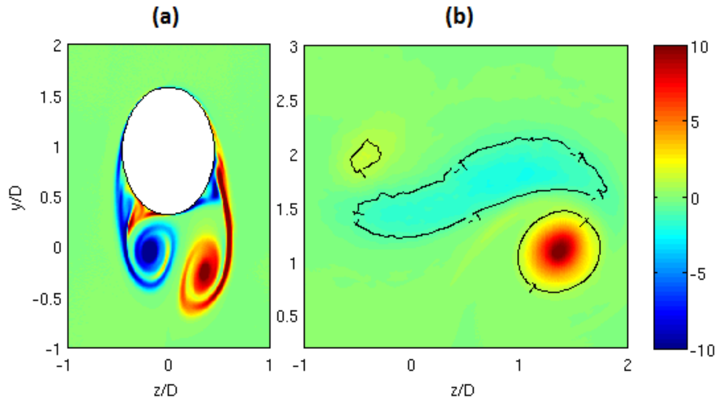

Figure 2. (a) $<\omega_x> D/U_0$ colour-contours at x/D = 1 (near-body wake); (b) $<\omega_x> D/U_0$ colour-contours at x/D = 5 (intermediate wake), together with black contour lines for $<\omega_x> D/U_0 = 1$ and -1.

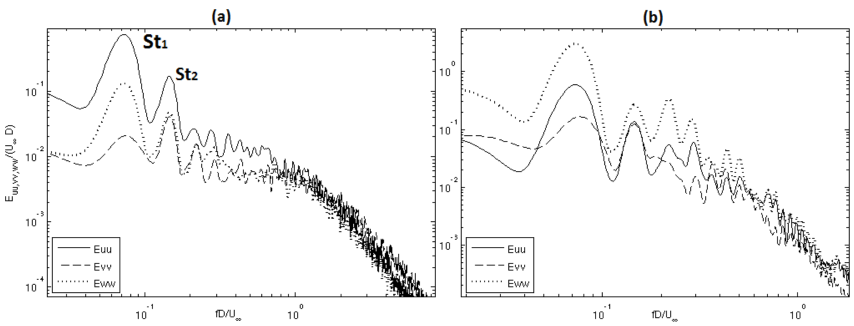

Figure 3. (a) and (b) show velocity spectra in all three directions at two different locations in the wake.

References

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