Modeling for the topology of coherent structures within a laminar separation bubble

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The large variation of lift and drag around a lifting profile, as a consequence of the flow transition and/or separation, has been widely investigated in recent years. Points of particular interest concern the accurate characterization of the flow separation and the laminar-turbulent transition evolution, being this knowledge a primary input for surface design and flow control and an accurate measure resolved in space and time is still an ongoing question. To this aim, the skin-friction estimation is one of the best suited candidates among those available in the experimental fluid mechanics, because of its implications in the understanding of laminar and turbulent boundary layer evolution and in the investigation of separation and laminar-turbulent transition [1]. Time resolved evolution of the skin friction lines can capture the loci of flow separation and reattachment in high detail (see e.g. [2]), conveying a straightforward portrait of critical points and lines on the model surface. Here we deal this subject with an experimental approach whose focus is on the skin-friction data derived from time histories of temperature maps obtained using Temperature Sensitive Paint (TSP) (see [1] for a description of the basic principles). We report a TSP application about a NACA 0015 hydrofoil tested in a water cavitating tunnel (CEIMM facility, Figure 1) at Re=[180k,360k,540k] and angles of incidence $\alpha \in [1°,10°]$, observed at a frame rate of 1KHz via a Photron SAX camera.

Figure 1: Sketch of the experimental setup at CEIMM (Rome-Italy). The hydrofoil model (orange) is placed in the middle of the tunnel and lighted with LED lamps. Its emission is acquired by a Photron SAX fast camera.

A region of recirculating flow was identified confined between laminar separation and turbulent reattachment points, which is commonly referred to as Laminar Separation Bubble (LSB). By following the approach proposed by Liu et al. [3] we extract wall quantities which allow for a topological description of the flow at the wall and shed a light in complex interactions of flow structures [4]. In this work the focus is placed on the topology of the coherent structures that appear in the reverse flow inside the recirculating region at different α. We assume that disturbances from shear layer above, which develops before the incoming laminar-turbulent transition, appear as impinging jets in the reverse flow region [2]. Then, by adopting a potential vortex model as corresponding induced flow field (see Fig. 2 left) and coupling it with a model of the flow in the reverse region (see Fig. 2 right and Figure 3), we identify and describe the raise, development and set of the associated coherent structures at the wall by comparing the results with the corresponding skin friction topology extracted from temperature maps [2]. Test cases are shown to report the interaction of such impinging jets against the separation line at AoA=10° (Fig. 4) and the development of omega-shaped, hairpin-like vortices in the reverse flow region at AoA=3° (Fig. 5). Here it is shown how the circulation of these latter is mirrored compared to the classical hairpin scheme of turbulent boundary layer, i.e. faster flow far from the wall is pushed down against the separation line towards the leading edge, thus inducing intermittent, highly energetic bursting phenomena involving the LSB dynamics.

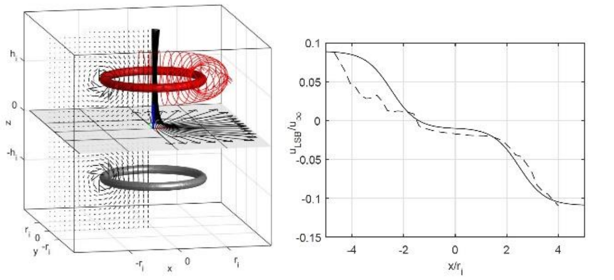

Figure 2: Left: potential vortex model. Right: flow velocity at the wall within LSB, measured (--) and modelled (-)

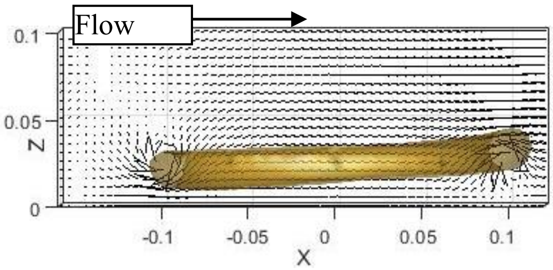

Figure 3: Coupling between potential vortex and reverse flow within the LSB. External flow is from left. Constructive flow coupling occurs toward the leading edge (towards the separation line). Destructive coupling occurs on the other side.

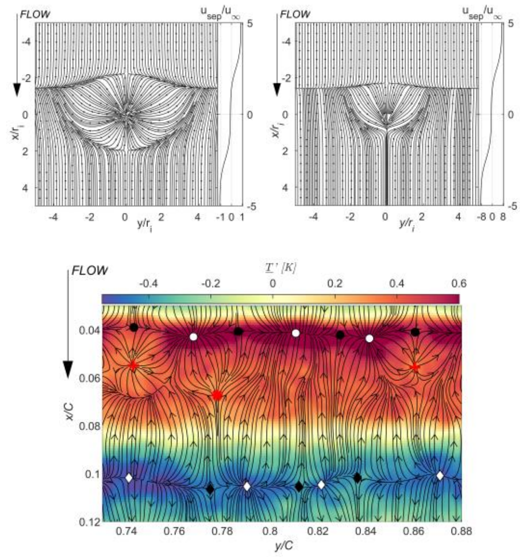

Figure 4 Skin friction lines from the coupled model (top) and from experimental data (bottom) for the flow at $\alpha = 10°$, Re=180,000. Saddle points (white) and nodes (black) are reported at separation (circles) and reattachment (diamonds).

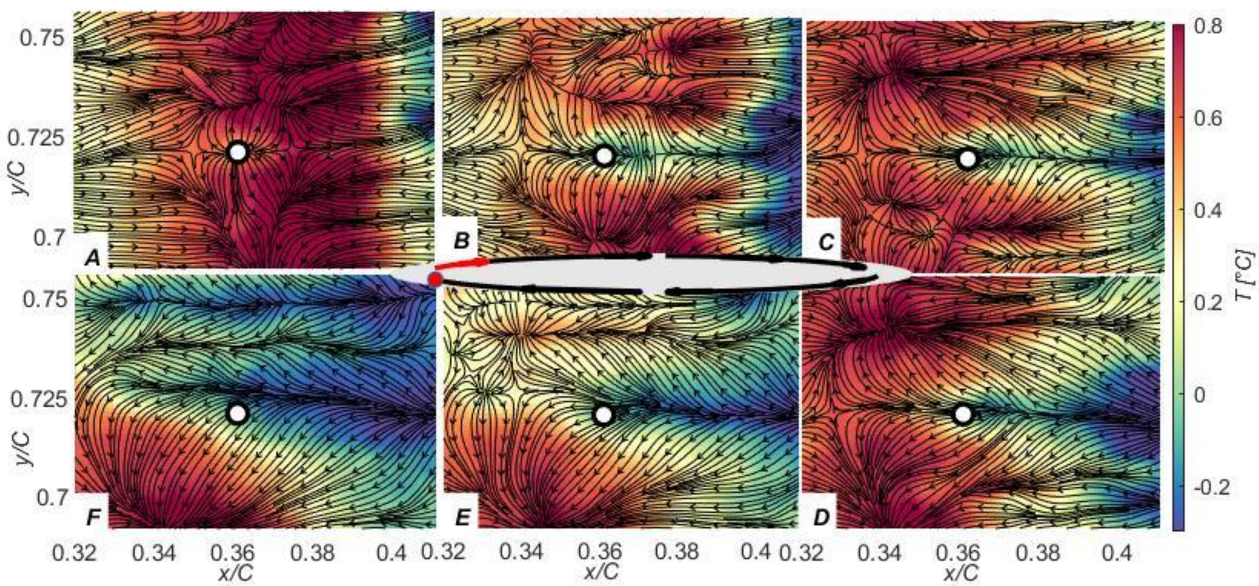

Figure 5: Raise, development and set of a hairpin-like vortex.

References

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