Biomimetic Design of a Vanishing Foil for Vehicle Super-Maneuverability

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Motivation and Experiment: Production of Large Maneuvering Forces

Swifts are amazing creatures that spend nearly their entire life in the air; these birds capture insect prey while flying, land only to breed and for the occasional roost (Holmgren, 2004), and spend up to the first three years of their lifetime airborne (Lack, 1956) . Not only are swifts highly aerial creatures, but they can also perform tight turns and fast maneuvers; the bird's wings are swept back during fast flight, but for rapid and tight turns the birds rapidly change their wing sweep, as shown in Fig. 1 (Muller and Lentink, 2004). This change in wing sweep is effectively a rapid change in the local cross sectional area of the wing. Spagnolie (2009) has also shown that a cylinder can accelerate in a fluid by changing its cross sectional area, where the forces associated with the changing shape are produced through an equivalent change in the added mass and subsequent shedding of vorticity.

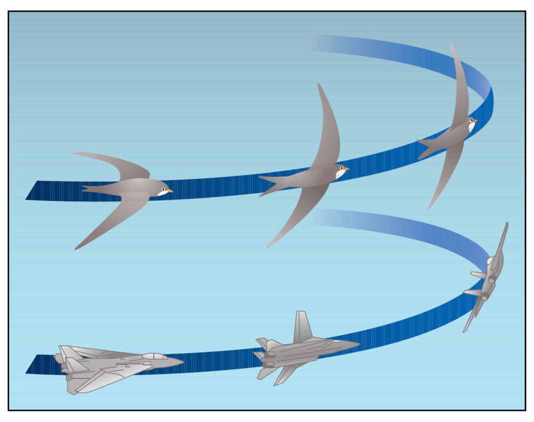

Fig.1: A swift rapidly changes its wing sweep to produce large forces for high performance tight maneuvering. Jet air craft use a similar principle for tight maneuvering. Adapted from Muller and Lentink (2004).

Rapid changes in surface and cross sectional area can produce large forces, which can then be used in extreme maneuvers. In our experiment we tow a NACA0012 cross section foil at a constant speed in a small water tank, rapidly retract the foil in the span-wise direction, and continue towing to the end of the tank, as shown in Fig. 2. A laser sheet illuminates the mid-retraction plane, for PIV analysis of a 2D slice where it appears that the foil cross section "vanishes" from view. We will see that as a result of the global and instantaneous shedding of the boundary layer vorticity, a foil that is towed and then rapidly retracted produces two vortices of unequal strength in the wake (Fig. 3). This instantaneously deposited circulation can be used as forcing for extreme maneuverability.

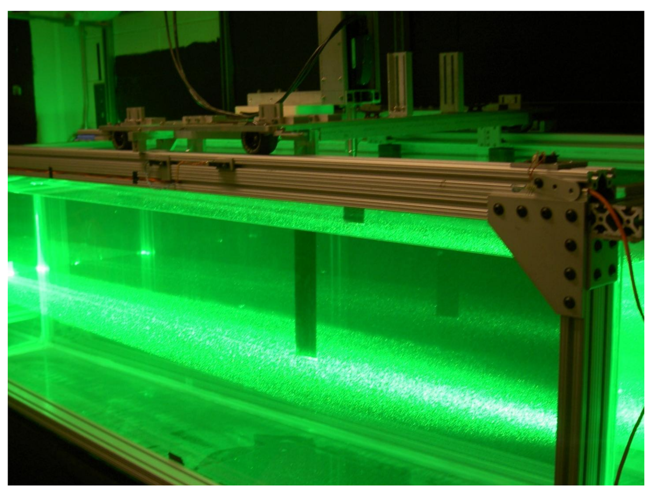

Fig. 2: Our experiment consists of towing a NACA0012 foil and then rapidly retracting the foil in the spanwise direction. Forward towing continues during and after retraction, and the laser sheet illuminates the mid-retraction plane.

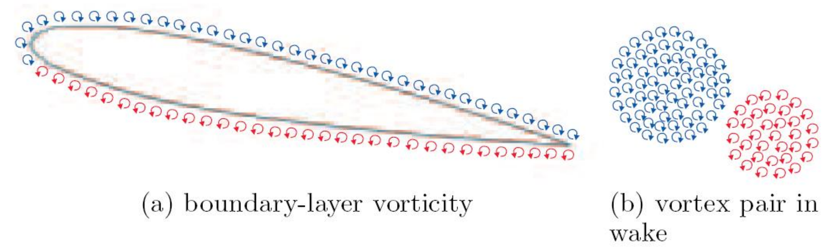

Fig. 3: The retraction of a towed foil results in the instantaneous and global shedding of the boundary layer vorticity (a), which stabilizes into two vortices left in the wake (b).

Global Vorticity Shedding: Vorticity Transfer into the Fluid

Looking through the time series of the PIV data, we are able to discover the vortex dynamics of our vanishing foil problem. In Fig 4. below, we study successive frames surrounding the vanishing point of the foil, with non-dimensional time $t^* = t\,(U/c)$ where time t is non-dimensionalized by towing speed U and foil chord length c. Time $t^* = 0$ denotes the instant our foil vanishes from the PIV plane, with negative t* indicating the presence of the foil cross section and positive t* indicating disappearance of the foil from the plane. The solid white denotes the foil cross section and the surrounding near-body field, with dashed line showing location of the foil (either in the PIV plane or above, when vanished). We have here the foil at 10 degrees angle of attack, moving right to left in a stationary fluid, with tick marks showing 0.2 chord lengths.

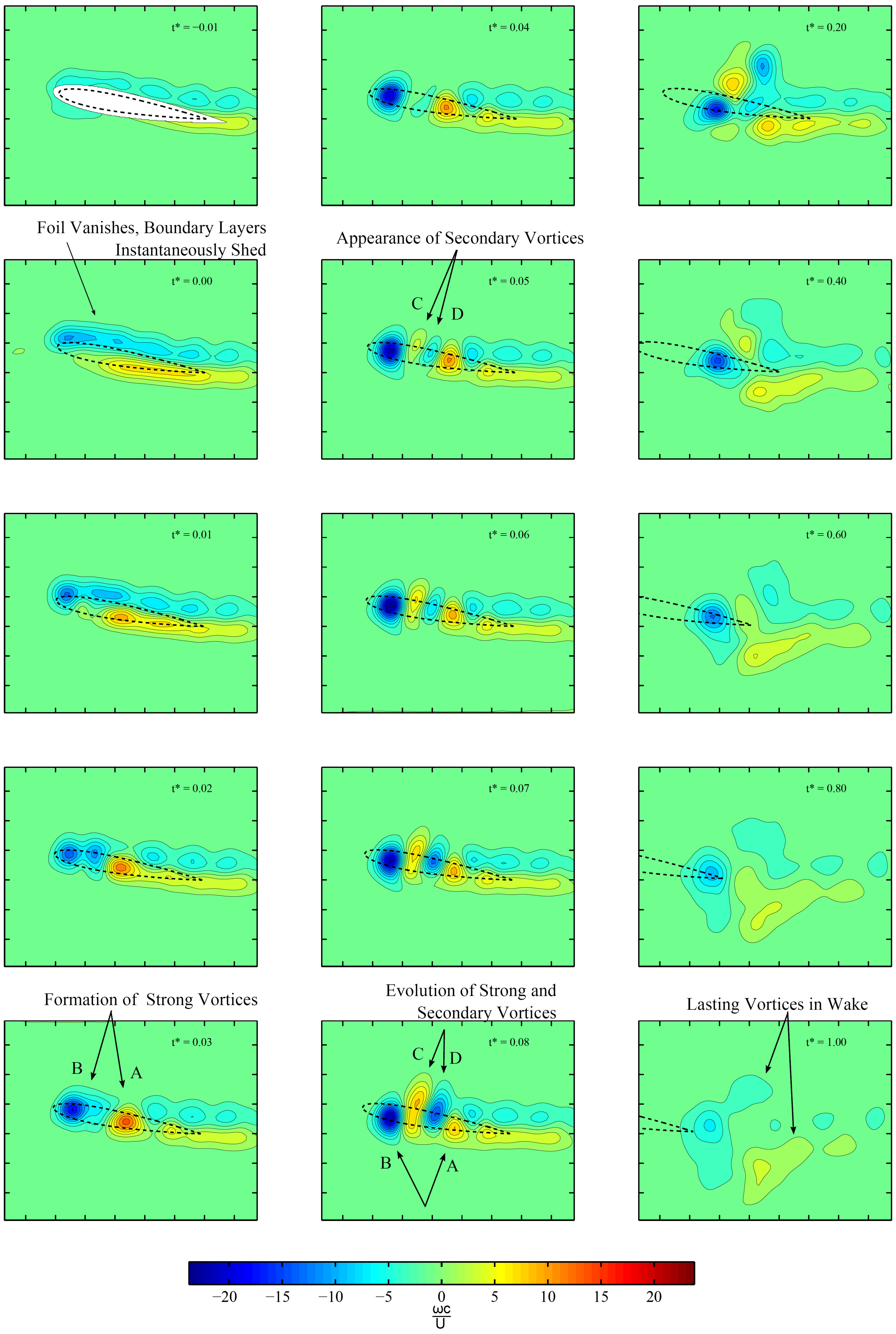

Fig. 4: Vorticity field for a foil at 10 degrees angle of attack as a function of t*. Foil vanishes and forms two free shear layers of unequal circulation at t* = 0, which then curl up into two vortices, A and B. Vortices C and D are caused by the entrainment and reconnection of vortices A and B to the foil at the connection of the tip vortex, which is all dragged upward through the PIV plane as the wing is rapidly pulled up. Ultimately, vortices A, B , C, and D recombine and form two lasting vortices in the wake.

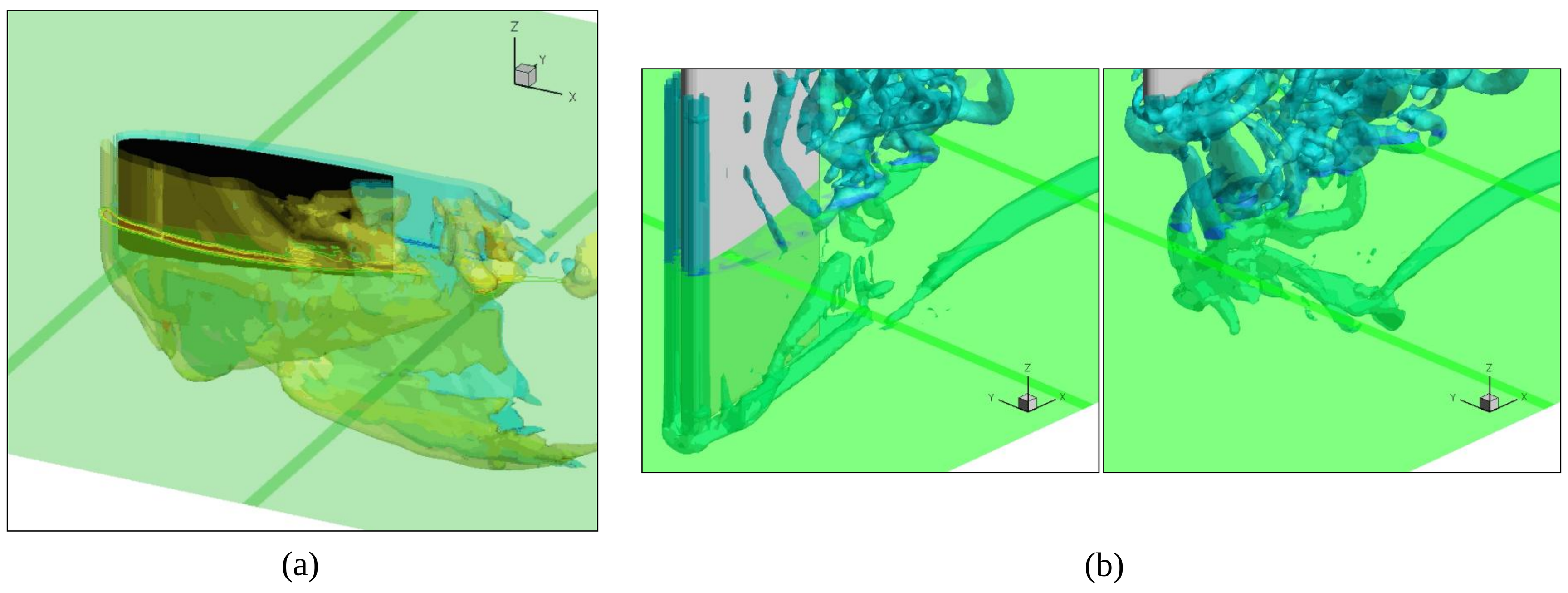

Fig. 5: 3D simulation of the foil at 10 degrees angle of attack, using Boundary Data Immersion Method (Weymouth and Yue 2011) and implicit large eddy simulation at Reynolds number 5,000; ~3.1M grid points with $dx = c/50$ and $dt = (c/U)/250$, where c is the chord length and U is the forward velocity. Z-vorticity plotted. (a) Outer curtains of positive and negative z-vorticity are globally shed and entrained as the foil retracts. Note the inner curtains are of opposite vorticity because the outer curtain wraps around and folds up as the foil vanishes and the fluid is entrained. (b) Iso-surfaces of the λ_2 = -100 metric of Jeong and Hussian (1995) indicate strong vortex cores in the wake of the foil. Note the strong tip vortex, leading edge vortices, and vortex loop connecting the tip vortex to the foil.

As seen in the 2D view (Fig. 4), the boundary layer first forms two strong vortices, A and B, that are disrupted by secondary vortices, C and D. These secondary vortices emanate from the connection of the tip vortex to the foil. The secondary vortices shoot out to the side, but are later pulled back in and recombine with the primary vortices to form two lasting vortices in the wake.

We can look to the 3D simulation (Fig. 5a) for another perspective. Here again, we can see the boundary layer vorticity sheets being left behind in the fluid as the foil vanishes, and we can also see here the corresponding 2D view with the green sheet representing the laser plane and cuts of the vorticity shown on the laser plane. The outer boundary layers also curl up when the foil starts to vanish and are entrained upwards, forming the inner vorticity sheets and are the origins of the secondary vortices C and D. Fig. 5b shows the strong vortex cores present in the simulation, before and during vanishing. Again, the green sheet represents the laser plane . We see very clearly here the tip vortex and the leading edge vortex, as well as some indication of the connection of the tip vortex to the foil.

Pressure Sensing for Rapid Maneuvering

We have seen that the vanishing of the foil in the two-dimensional plane, or the rapid change in surface and cross sectional area, results in the rapid and global shedding of the boundary layer vorticity. This instantaneously shed vorticity forms into two lasting vortices of unequal strength in the wake. By rapidly vanishing the foil, we have essentially freed the bound circulation, quickly introducing useful circulation into the fluid.

We foresee that this rapidly deposited circulation can be used to produce large forces for rapid maneuvering in underwater vehicles. Moreover, the work being done here at CENSAM will allow for pressure sensing feedback capabilities in conjunction with this type of super-maneuverability actuation. We have seen in previous and ongoing work that solid objects can be detected through flow pressure sensing, and could be combined with a rapid maneuver mechanism in order to trigger a rapid maneuver for object avoidance. In addition, it may be advantageous to trigger a rapid maneuver in favorable flow conditions, such as taking advantage of a vortex already present in the fluid passing near the body. Together with a high performance maneuvering mechanism based on this research, pressure sensing feedback could greatly enhance a super-maneuverable system.

Acknowledgements

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