

11 Conclusions

Experimental and numerical investigations into the vortex dynamics associated with tandem-airfoil configurations, i.e. dragonfly flight, have been performed. Reynolds numbers ($3000 \leq Re \leq 30000$) and reduced frequencies ($0.25 \leq k \leq \infty$) corresponding to dragonfly flight at both cruise and hover conditions have been selected for the various studies. The focus here has been placed on the formation of leading-edge vortices (LEVs) and trailing-edge vortices (TEVs) generated by the forefoil, as well as their interactions with the hindfoil in the wake. Particle Image Velocimetry (PIV), in both standard and time-resolved form, and to a lesser extent direct force measurements, were used in the experiments. Subsequent analysis of the resulting PIV velocity fields was made using vortex-tracking, pressure-integration and control-volume analyzes allowing for a detailed understanding of the vortex dynamics, blade-vortex interactions and induced forces, respectively.

In this chapter the goal was not to reiterate the conclusions made in the individual results sections; these can be found in the summary sections at the end of each chapter. Rather the goal here was to summarize, in a succinct fashion, the lessons learned regarding these simplified investigations of dragonfly flight. First the major conclusions related to a single airfoil and its associated vortex development are presented. Thereafter conclusions pertaining to vortex dynamics and energy capture in tandem configurations are made.

The most salient observations corresponding to vortex formation and manipulation over a single airfoil are the following:

- At the low reduced frequencies tested in the wind tunnel ($0.05 \leq k \leq 0.3$), large overshoots in lift, drag and moment due to dynamic stall are observed. Although at higher reduced frequencies ($k > 0.2$) a mushroom-wake is observed with a corresponding single LEV-TEV vortex pair, thrust-production is not yet present;
- When varying the plunge kinematics to non-sinusoidal motions, LEV formation is strongly influenced, i.e. the timing relative to the airfoil position in the stroke can be adjusted. However, maximum LEV circulation and hence formation number are limited to $4.4 < \hat{\Gamma} < 5.0$ corresponding to theory, as reported on by Dabiri (2009). This suggests that an LEV can be sustained over a two-dimensional airfoil for longer periods without the requirement of a span-wise flow for stabilization, contrary to the arguments of Ellington (2006);
- The superposition of a quick-pitch motion near the bottom of the stroke can be used to reduce or even eliminate the TEV without greatly affecting the LEV circulation. These kinematics have the potential of increasing lift and reducing the force hysteresis by reducing the size and duration of the separated flow over the airfoil.

From the tandem-airfoil investigations, the following major findings regarding vortex dynamics and energy capture have been made:

- For a static hindfoil placed in the wake of a plunging airfoil (forefoil), i.e. wave-propeller configuration, the vortex formation process over the forefoil is affected such that maximum LEV circulation is substantially increased. Formation numbers of $\hat{T} \geq 6.0$ have been measured and are even higher when the hindfoil is moved in the wake. This increase in formation number is analogous to the work on vortex rings by Dabiri (2005) and Shusser et al (2006), and shows a strong upstream coupling in the tandem-airfoil interaction.
- When further examining these tandem configurations in cruise conditions, net thrust is observed only at an airfoil phasing of $\psi = 60^\circ$, in agreement with the studies of live dragonflies made by Azuma (2006). This clearly shows that two drag-producing airfoils, when brought in close proximity, are capable of generating a net thrust. This synergy is analogous to the cylinder-foil experiments based on swimming trout of Gopalkrishnan et al (1994) and Beal et al (2006). With the help of CFD, the thrust-producing mechanism has been uncovered, consisting of a leading-edge suction bubble on the hindfoil. This small yet effective suction region is induced by the passing of the forefoil's LEV downwash.
- Despite distinctive suction peaks on the hindfoil produced through strong blade-vortex interaction, no net lift augmentation over the cycle was measured. The initial increase in suction through vortex-induced separation generated by the passing TEV was canceled out by the slow reattachment period. Despite this drawback in net lift production, the CFD analysis identified a power reduction for the hindfoil upstroke due to normal suction associated with the vortex-induced separation phenomenon.
- The investigation of hovering has revealed a completely different aerodynamic mechanism to that described above for cruise conditions. Here, the shed TEV from the forefoil influences the development of the hindfoil LEV. This LEV in turn acts to reposition the hindfoil TEV, which for such cases is primarily responsible for thrust generation. An airfoil phasing of $\psi = 90^\circ$ has been found to generate similar levels of thrust and power consumption when compared to a single airfoil. However, for the tandem arrangement, thrust production is found to be more constant throughout the cycle whereas power consumption is reduced for the first half-cycle and increased over the second half-cycle.
- This mechanism for hovering dragonfly flight corresponds with the findings of Azuma (2006) for live dragonflies as well as with the force measurements of three-dimensional flapping wings by Lehmann (2009), suggesting that the dominant mechanism associated with dragonfly-wing interaction is in fact two-dimensional after all. This finding again supports the argument that a span-wise flow is not necessarily required for efficient vortex control but rather a result of the evolutionary restrictions in nature towards root-flapping flight.

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