Abstract

The efficient flight of natural flyers has guided recent advancements in the design of micro-aerial vehicles (MAVs), particularly in low Reynolds number regimes. Dragonflies, known for their thin, corrugated wings and gliding ability, provide key insights for fixed-wing, also inspire energy-efficient gliding adaptations in flapping-wing MAVs development. However, the aerodynamic influence of the spacing between the fore and hind wings remains largely unexplored. In addition, turbulence effects are vital to consider for MAVs and insect-inspired flyers in outdoor environments. Despite several studies on insect-inspired flapping flight, limited work has been done on the glide mode of flight to understand the aerodynamic behavior of corrugated wing structures under turbulent and three-dimensional flow conditions at low Reynolds number.

Corrugated airfoils trap vortices in recirculation zones where turbulence models often fail, which makes direct numerical simulation essential to accurately capture transition, separation, and reattachment. In order to reduce the computational cost, we propose to perform a direct numerical simulation within a truncated subdomain constraint using a Reynolds-averaged Navier-Stokes solution. A criterion for the ideal truncated domain size is determined, producing equivalent results with respect to Direct Numerical Simulations over a large domain with conventional boundary conditions.

First, we applied this method to study the flow interaction over corrugated edges at a low Reynolds number of 10^4, to understand the aerodynamic effects of corrugation. The results disclose that the leading-edge vortex destabilizes the flow early on and subsequently interacts with the downstream corrugated peaks, promoting turbulence and helping to prevent flow separation further downstream. We extended the study to assess the corrugated airfoil in a tandem configuration for different horizontal and vertical offsets. The result reveals the optimized position of the tandem wing positioning while employing the glide mode of flight. A comparative study with a smooth profile airfoil reveals the potential advantage of corrugation over a smooth profile.

Finally, we incorporated synthetic turbulence in the inlet flow field effect of turbulence on the corrugated profile compared to the smooth-profile airfoil. Dynamic mode decomposition shows that the corrugated wing exhibits a broader range of energetic modes than the mode-dominated NACA profile under turbulence, indicating more complex flow structures and better disturbance dissipation for the corrugated airfoil. The dragonfly with its corrugated tandem configuration provides good aerodynamic efficiency (~ 10), and its turbulence resilience, enhanced by corrugation, indicates the importance of the corrugated wing in the natural selection of dragonflies.

Keywords: Bio-inspired airfoil; Direct Numerical Simulation; Dragonfly; Low Reynolds number; Tandem airfoil.