Virtual Shape Definition of Very Low Reynolds Number Airfoils Using Vortex Shedding

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I. Introduction

Over the last decade, aerospace engineers have been challenged to design aircraft that are as small as possible for special, limited-duration military and civil missions. These so-called micro-air vehicles (MAVs) have become of interest because electronic surveillance and detection sensor equipment can nowadays be miniaturised so that the entire payload mass is below 20 grams. The advantages of MAVs include low-cost production, compactness, transportability, rapid deployment, real-time data streaming, and the difficulty to see, hear, and detect them. Their potential applications cover military reconnaissance, search and rescue, and other missions which could benefit from sensing technology being deployed into a small, cramped area. One way of designing efficient MAVs is by bio-mimeticism. Among natural flight systems, large dragonflies (Anisoptera) are capable of carrying out incredible flight manoeuvres. These include hovering and flight in multiple directions. Even gliding, which is seldom found in the insect world, is part of their flight regime. A small vehicle with the flight capabilities of a dragonfly could therefore execute multiple, dissimilar mission roles at once. While the technology required to enable this is still a long way off, a first step forward is to gain an understanding of the biological dragonfly flying system and to develop methods for mimicking it aerodynamically. In this paper, we focus on the gliding flight regime of the dragonfly with the aim to transfer any beneficial feature into the wing design of fixed-wing MAVs.

Dragonfly wings are not smooth or simple cambered surfaces. Instead, the wing section has a well-defined corrugated configuration (Figs. 1 and 2). This design is of critical importance to the static aeroelastic stability of this ultra-light construction. However, from an aerodynamic point of view, this sawtooth single-surface airfoil does not appear to be very suitable. The pronounced bends and edges should lead to high drag values due to vortex shedding around the sharp corners (more kinetic energy given to the surrounding air). However, in visualizing experiments using profile models, Refs. 8–10 have shown that this geometry induces positive flow conditions. It has been speculated that eddies shed in the troughs help keep the flow from separating. As a matter of fact, Kessel claims that “the eddies filling the profile valleys formed by these bends ‘smooth down’ the profile geometry.” If this is really the case, one can then hope to define a virtual streamlined shape from a corrugated structure. Moreover, in the context of morphing aircraft, where one seeks to have continuous adjustments in the shape of the wing for more efficient flight control or mission adaptation, the limiting factor is often the skin of the airfoil which must comply with the displacements of the underlying morphing structure. In the case of virtual airfoil shape, that limitation disappears. The benefits of virtual shape definition by vortex shedding around a corrugated structure at low Reynolds number are therefore twofold:

- potential ability to sustain an attached flow (outside the corrugation troughs) at low Reynolds numbers where conventional airfoil shapes would experience laminar flow separation or large laminar bubbles;
- easier continuous adjustments of the shape for optimal aerodynamics with respect to the current flight condition.

Our investigation of the corrugated airfoil aerodynamics is conducted in three primary stages. Firstly, numerical simulations of the laminar, transient airflow around the profile lying between the subcosta and the...
radius of the dragonfly wing (see Figs. 1 and 2) are carried out in order to get a deeper understanding of what happens in and around the corrugations. For comparison purposes (in terms of aerodynamic performances), the airflow around Mueller’s C4 airfoil (Fig. 3), a wing section shape commonly used in MAV design, is computed for the same operating conditions. Secondly, numerical parametric studies are performed with respect to the Reynolds number, corrugation depth, and camber, to help identify beneficial strategies of morphing for flight control and/or mission adaptation. The third and final stage of our investigation is concerned with the influence of 3D effects on the aerodynamics of low aspect ratio wings at low Reynolds numbers, where the wings of interest are lofted with the profiles studied in the first stage (only low aspect ratio wings are considered since those are typical for MAVs).

II. Computational Set-Up

A. Numerical Flow Solver

To provide performance estimates, we rely on a cell-centred, finite volume approximation of the time-dependent Navier-Stokes equations for laminar, incompressible flow. The open-source field operation and manipulation (OpenFOAM\textsuperscript{14}) C++ class library for continuum mechanics is used for solving the resulting algebraic equations on a collocated, unstructured grid by means of a projection method, where the PISO algorithm\textsuperscript{15} enables the pressure-velocity coupling between momentum and continuity equations. The following discretisation schemes are selected so as to ensure a global second order accuracy in space and time:

- The time derivative is approximated by a second-order accurate, backward discretisation;
- The convected variables and mass fluxes are interpolated at the cell face centres using second-order accurate central discretisation;
- The cell-centre gradients are obtained from a second-order accurate, distance-weighted, least-squares approximation;
- The face-centre surface normal gradient is approximated by a second-order accurate central finite difference scheme involving the values at the centroid of the adjacent cells (in the case of non-orthogonality between the adjacent mesh cells, an explicit non-orthogonal correction based on the face-interpolated cell-centre gradients is performed).

B. Computational Grid Systems

The 2D computational grid system is generated by using Delaunay’s triangulation technique. The outer boundary is located 50 chords away from the airfoil centroid. A uniform spacing of 0.001c, where c is the airfoil chord, is used to discretise the edges forming the airfoil surface. At the investigated chord Reynolds numbers (Re\textsubscript{c}), ranging from $10^3$ to $10^4$, the distance from the airfoil surface to the first off-wall grid points is then smaller than $c/(6\sqrt{Re_c})$, which is more than enough to properly resolve the laminar boundary layer. Fig. 4 shows the near-field mesh around the dragonfly airfoil and one of its ‘cambered’ versions. To be consistent with Mueller’s C4 airfoil, the thickness of the linear elements defining the corrugations of the dragonfly wing section represents about 2% of the chord length. One can notice the high density of cells in and around the corrugations. This is done on purpose so as to capture accurately any vortex shedding, which is the physical phenomenon driving the aerodynamics of the corrugated wing section. The total number of cells for the baseline 2D grid system is about $10^5$.

The 3D grid system is obtained by generating a 2D triangular mesh of limited extend around the airfoil (i.e. within a box of two-chord length and one-chord height), which is then extruded in the spanwise direction, from the wing root to the wing tip. Tetrahedral elements, along with a pyramid layer to transition from the spanwise prismatic elements, are used to fill the rest of the computational domain, whose far-field boundary is located 50 chords away from the wing centroid. Since only symmetric flow conditions are investigated, only half the wing is modelled and a symmetry boundary condition is used at the wing root plane. The total number of cells (including prisms, pyramids, and tetrahedra) for the baseline 3D grid system is about $10^6$. 

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III. Results and Discussion

A. Aerodynamic Properties of the Dragonfly Inner Airfoil

Bidimensional, planar flow simulations around the dragonfly wing section of Fig. 2 and, for comparison purposes, Mueller’s C4 airfoil (Fig. 3) have been carried out at several angles of attack, ranging from $-5^\circ$ to $40^\circ$ (measured with respect to the chord line joining the leading and trailing edges), for a Reynolds number of 1000, which corresponds to the gliding flight regime of the dragonfly. After a physical time long enough for the flow to forget about the initial conditions, each simulation reaches a fully developed state, either steady or periodic.

Streamlines around the dragonfly wing section are plotted in Fig. 5. One can notice that the hypothesis of eddies filling the troughs of the corrugation is indeed true. As hypothesised, the eddies ‘smooth’ the shape of the corrugated structure, as the flow pattern outside the corrugation resembles the one around a streamlined body.

When the angle of attack increases (above 10 deg.), vortex shedding becomes more significant, as demonstrated by the instantaneous pressure field from Fig. 6. This makes the flow past the corrugated dragonfly airfoil unsteady, yet periodic, see Fig. 7. Let us mention however that the cambered plate airfoil (Mueller’s C4) exhibits the same kind of unsteadiness (not shown here), indicating that the vortex shedding is more a matter of Reynolds number rather than corrugation.

Fig. 8 compares the drag polar of both the airfoils at $Re_c = 1000$ (plotted values are averages over one vortex shedding period, the horizontal and vertical bars centred about each computed point represent the drag and lift RMS values). One can see that for lift coefficients greater than 0.5, Mueller’s airfoil is clearly more efficient than the dragonfly airfoil.

B. Influence of Reynolds Number

It has been observed that increasing the Reynolds number to $5 \times 10^3$ at fixed angle of attack strengthens the intensity of the free vortices, leading to larger amplitudes in the oscillations of the aerodynamic forces. Increasing the Reynolds number further to $10^4$ triggers significant noise in the time history of the aerodynamic coefficients (not shown here), suggesting the flow may be transitional at that particular Reynolds number. This has been confirmed with subsequent computations with Xfoil$^{16}$ for Mueller’s C4 airfoil: Xfoil locates the transition at mid-chord on the upper surface at a $10^\circ$ angle of attack for $Re_c = 10^4$. In the remainder of the paper, only $Re_c = 10^3$ flows are considered.

C. Influence of the Corrugation Trough Depth

The corrugated airfoil geometry from Fig. 2 is scaled up by 1.33% along the vertical direction only (i.e. normal to the chord axis), which gives deeper corrugation troughs. The drag polar of this modified airfoil is plotted for $Re_c = 10^3$ in Fig. 9, along with the drag polars of the original airfoil and the cambered plate for comparison purposes (for the sake of clarity, RMS lift and drag values are omitted for the cambered plate) one can observe that the main effect of the modification is to increase the efficiency of the corrugated airfoil (i.e. less drag for the same amount of lift) for lift coefficients greater than 1. The so-modified corrugated airfoil even becomes better than the simple cambered plate (Mueller’s C4 airfoil) at higher angles of attack, e.g. for lift coefficient greater than 1.5.

D. Effect of Camber Change

In the frame of morphing for mission and/or morphing for control, it is interesting to study how the wing section aerodynamics changes with an increased camber. In our case, we choose to increase the camber of the original dragonfly airfoil by performing two successive deflections: 1) a first deflection about the 4th bend apex, and 2) a second deflection about the 5th bend apex. Fig. 10 depicts the cambered, corrugated profiles obtained by applying either two deflections of 10° or two of 20°. Drag polars for these two new configurations are plotted in Fig. 11, along with the drag polars of the unmodified corrugated airfoil and Mueller’s C4 airfoil (for the sake of clarity, the RMS bars are omitted). As far as the modified corrugated airfoil featuring two 10° deflections is concerned, it offers similar performances as the undeflected modified corrugated airfoil for lift coefficients smaller than 0.5 and greater than 1.5 (with a slight advantage towards the undeflected airfoil though); however, for lift coefficients between 0.5 and 1.5, it outperforms significantly
the undeflected airfoil. Furthermore, it performs better as well than Mueller’s C4 airfoil as soon as the lift coefficient becomes greater than one. Increasing further the camber does not bring additional benefits, on the contrary it penalises the airfoil at lower lift coefficient because of the extra drag associated with a more pronounced camber (see cambered, modified airfoil #2 in Fig. 11).

E. Three-Dimensional Effects

So far, our investigation assumed two-dimensional planar flow. However, low Reynolds number flows are highly three-dimensional in essence, which is aggravated by the dragonfly wing geometry itself, where the corrugation pattern changes from one spanwise station to the other (see Fig. 1). It makes therefore sense to argue that our previous findings based on 2D flow simulations may not hold for a real dragonfly wing, and that 3D effects could be beneficial (or detrimental) to its aerodynamic performance when compared to the plain cambered plate of finite span. To settle this speculation, we decide to investigate untwisted wings of square planform (i.e. aspect ratio of 1), obtained by extruding either the unmodified corrugated dragonfly profile or Mueller’s C4 profile. The choice of such a planform is not arbitrary but based on the following two considerations: 1) such a small aspect ratio promotes 3D effects, and 2) MAV wings, which are of interest in this study, have an aspect ratio of the order of 1.

Fig. 12 shows the drag polars predicted for the corrugated wing and the cambered plate, for angles of attack ranging from 5° to 20° with 5° increments. In contrast with the 2D cases, the unsteadiness of the flow past the square wings is not very pronounced, even for angles of attack greater than 10°. In fact, only the corrugated wing shows some noticeable unsteadiness at 20° angle of attack, but not as much as in the 2D case though. In the like of the 2D cases, the corrugated wing based on the unmodified dragonfly wing section is outperformed by the simple cambered plate which can reach higher lift coefficients, and produce less drag for the same lift. In that respect, we can say that the corrugated structure aerodynamics does not benefit, as it was hoped, from 3D effects.

IV. Conclusion

We investigated the aerodynamics of the inner wing section of a dragonfly forewing and compared its performance in the gliding flight regime to a thin, circular-arc airfoil. It appeared, from two- and three-dimensional simulations that the latter outperforms the dragonfly wing section. However, adding some camber to the original dragonfly wing section and deepening the trough of its corrugations made it superior to the cambered plate for moderate to high angles of attack. Considering the fact that the dragonfly wing section shape we studied was extracted from an unloaded, dry wing, it is reasonable to assume that the shape of such a membrane wing will be quite different when loaded. Therefore the predicted performance of the unmodified unloaded shape are not very indicative of the real potential of a dragonfly wing section. Nevertheless, we demonstrated that, by applying elementary deformations to such a wing, better performances could be attained and that they could match those of a typical thin airfoil used in MAV design. Whether these deformations are the same or not as the ones undergone by the real membrane wing of the dragonfly remains an open question though.

V. Acknowledgements

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References


Figure 1. Drawing of a dragonfly forewing (Aeshna cyanea) with wing sections shown below at 0.3\(l_{rel}\), 0.5\(l_{rel}\) and 0.7\(l_{rel}\), where \(l_{rel}\) denotes the wingspan. C, costa; SC, subcosta; R, radius; N, nodus; M, mediana 1. Taken from Ref. 13.

Figure 2. Wing section profile of a dragonfly forewing at 30\% wingspan.

Figure 3. Mueller’s C4 airfoil, a 1.93\% thick, cambered plate with tapered trailing edge and circular arc shape of 4\% camber (from Ref. 1).

Figure 4. Computational grids around original (left) and morphed (right) dragonfly airfoils.
Figure 5. Streamlines around the airfoil forepart at 0 deg angle of attack and Re=1000.
Figure 6. Contours of the pressure coefficient at different instants over a vortex shedding period ($\alpha = 10^\circ$; $Re=1000$; period $T$ is $1.2c/U$, where $U$ is the freestream velocity).
Figure 7. Force history for the dragonfly airfoil at 10 deg, 20 deg, and 30 deg angle of attack (Re = 1000).

Figure 8. Drag polars of the dragonfly wing section and Mueller’s C4 airfoil (Re = 1000).
Figure 9. Drag polars of Mueller’s C4 airfoil, the original dragonfly wing section, and the modified dragonfly wing section (Re = 1000).

Figure 10. Geometries of the modified dragonfly wing sections.
Figure 11. Drag polars of Mueller’s C4 airfoil and the modified dragonfly wing sections (Re = 1000). ‘Modified airfoil’ refers to the uncambered airfoil with 1.33% deeper corrugation troughs; ‘modified, cambered airfoil #1’ refers to the modified airfoil after 2 deflections of 10°; and finally ‘modified, cambered airfoil #1’ refers to the modified airfoil after 2 deflections of 20°.

Figure 12. Drag polars for the square cambered plate (Mueller’s C4) and the square corrugated plate (dragonfly wing section) at Re = 1000.