Chapter 9

Conclusions and Perspectives

9.1 Conclusions

In the last years, significant progress has been made in the understanding of the major aerodynamic features of flapping airfoils/wings by using experimental and computational approaches. Much of the work done by researchers has been focused on two-dimensional flapping airfoils and, as one would expect, the information available on three-dimensional flow features and aerodynamic performance of finite-span span wings is quite limited. This limitation is mainly due to the unsteady nature of the flow and the requirement of high resolution in regions of flow separation, vortex shedding and vortex wake evolution, which, added to the requirement of bigger and finer computational domains render three-dimensional simulations of flapping wings a very expensive problem from a computational point of view. Clearly, the flapping wing mechanism that has evolved in nature presents many interesting challenging problems. Platzer *et al.* [145], addressed the challenges that still remains open or need to be investigated more deeply for a complete understanding of flapping airfoils and wings aerodynamics. In [145] they listed the following areas of research:

1. Most flapping airfoil/wing propulsion computational studies and experiments have been limited to symmetrical NACA airfoils, or to a lesser extent, elliptical airfoils. The effect of airfoil geometry, remains to be systematically explored. Of particular importance is the physics governing the onset of vortex shedding from the leading edge and their interaction with the trailing edge vortices.
2. The three-dimensional flow features generated by finite-span wings present a great challenge due to the effort to visualize, measure and compute the complex flows generated by flapping wings. Of special importance are the spanwise flow features which may include the formation and shedding of spanwise vortices.
3. Flapping wing propulsion in nature involves flexible wings. However, the physics of the flow over flexible flapping wings is yet to be fully understood. Advances have to be made through carefully designed experiments and the development of flow solvers that incorporate efficient and effective fluid-structure coupling.
4. One key application of studying flapping wing aerodynamics is the determination of the conditions for *"optimal"* aerodynamic performance in terms of lift, thrust and propulsive efficiency. Despite substantial research efforts, there is still a lack of full understanding of the physics governing the *"optimal"* aerodynamic performance of flapping wings. Important

parameters that influence the aerodynamics of flapping wings include the shape of the wing, the stiffness of the wing, the type of flapping motion and Reynolds number.

5. Modeling of transition from laminar to turbulent flows is very difficult even for fixed wings applications. Detailed experimental information is needed on the formation of separation bubbles. Although considerable progress has been made in this area for steady airflow flows, very little is known about the behavior of separation bubbles on oscillating airfoils. It is inevitable that advances in separation bubble formation and transition flow modeling are required before the benefits of flapping wing propulsion can be fully exploited.

In this dissertation, we attempted to address most of the previous challenges, in order to contribute to a better comprehension of the mechanism of flapping airfoils/wings propulsion and the associated unsteady aerodynamics, independently of their possible practical applications.

In chapter 7, we explored the wake structures and aerodynamic performance of flapping airfoils. We studied the dependency of the wake structure and aerodynamic performance on the flapping and geometric parameters such as flapping frequency and amplitude, airfoil geometry and airfoil chord-wise flexibility, for airfoils undergoing pure heaving motion or flapping motion. All the qualitative and quantitative results presented in this chapter support the hypothesis that : *"flying and swimming animals cruise at a Strouhal number tuned for high power efficiency"* [182]. The enhanced efficiency range was found to be between Strouhal number values corresponding to $0.2 < St < 0.4$, with a maximum efficiency peak at approximately $St = 0.3$, which agrees with the observations of Nudds *et al.* [136], Rohr and Fish [155], Taylor *et al.* [182] and Triantafyllou *et al.* [193].

In that chapter, we assessed also the validity of the Strouhal number St as the fundamental aerodynamic single parameter insofar as high propulsive efficiency is concerned. It was found that St seems to be enough for wake signature characterization, but is not sufficient insofar as maximum efficiency is concerned. Both heaving amplitude h_a and heaving frequency f_h (hence the Strouhal number St and the reduced frequency k) should be adjusted separately.

The wake topology of a heaving airfoil was also characterized for a wide range of heaving amplitudes and heaving frequencies combinations. The wakes were classified as drag producing, neutral, thrust producing, deflected wake and jet-switching wake. It was found that the deflected wake topologies were highly reproducible and they were mainly found in a range of Strouhal number values between $0.5 < St < 0.8$. At higher St values, we encountered the aperiodic jet-switching wake, but we were not able to determine if the switching is random or periodic, basically due to the fact that the simulations have to be run for extremely long times in order to observe the onset of the jet-switching. It is important to mention that as far as the author is aware, very limited experimental and computational information exist on the jet-switching phenomenon; therefore, much work remains to be accomplished in this area. The reason for the deflected wake and jet-switching phenomenon seems to be the interaction of the vortices shed at the trailing edge at the high St where these phenomena are encountered.

Different behaviors on the aerodynamic performance for high flapping frequencies (low heaving amplitudes) and low flapping frequencies (high heaving amplitudes) were also observed. Firstly, at high flapping frequencies the LEV does not have sufficient time to grow, whereas at low flapping frequencies the vortex has a size which is a sizable fraction of the airfoil chord, before separating.

Thus the impact of the vortex on the pressure at the nose of the airfoil is dependent on the flapping frequency. Secondly, once the vortex separates it is convected downstream over the surface of the airfoil. Due to the low pressure in the vortex core this has the effect of maintaining thrust while the vortex is upstream of the airfoil maximum thickness point (where the airfoil surface is tilted upstream and the vortex low pressure creates an upstream suction force). Once passing this point, the airfoil surface is tilted downstream and the vortex contributes to drag rather than thrust. At high flapping frequencies, the vortex cannot be convected far downstream before the motion cycle creates another leading edge vortex on the opposite side of the airfoil, so the impact is lessened. At low flapping frequencies however, the vortex travels far downstream over the airfoil surface causing drag for a larger portion of the flapping cycle and therefore lowering the propulsive efficiency. For flapping motion, where the orientation of the airfoil surface is controlled by the relative amplitudes and phases of the motion, the LEV may create positive thrust for much longer portions of the flapping cycle and thus contribute towards the propulsive efficiency. Also, for flapping motion the average input power coefficient is less than the average input power coefficient for the heaving motion cases, resulting in an improved propulsive efficiency. It was also observed that the best propulsive efficiencies were obtained for high heaving amplitudes (between $0.8 < h_a < 1.2$), in contrast to the heaving motion were the propulsive efficiency is deteriorated as the heaving amplitude is increased above a value of $h_a = 0.2$.

In chapter 7, we also studied the effect of chord-wise flexibility on the aerodynamic performance of heaving airfoils. Thrust-indicative wake topologies were observed for the whole range of flexure amplitudes tested. The results have also shown that the propulsive efficiency is enhanced for values of $h_{flex} < 0.4$. This observation is in agreement with the results of Heatcote and Gursul [67, 68], where they found that adding a degree of flexibility increases both thrust and propulsive efficiency. They also suggested that birds, bats and insects may benefit aerodynamically from the flexibility of their wings.

Finally, the effect of airfoil cambering on the aerodynamic performance was assessed. It was found that this geometric parameter has a strong influence on the lift coefficient, while it has a small impact on the thrust coefficient and propulsive efficiency. Among all the asymmetric airfoils used, the NACA 6612 airfoil provided the best propulsive efficiency and average lift coefficient, which, along thrust generation, are the crucial factors if we are interested in flapping flight. The S1223 airfoil, which resembles the cross-section of the Seagull and Merganser wings (as observed by Liu *et al.* [114]), provided at high heaving frequencies the biggest average lift coefficient and very similar average thrust coefficient and propulsive efficiency values when compared to the other airfoils. On the other hand, at low heaving frequencies, the aerodynamic performance of the S1223 airfoil was deteriorated in comparison to the other airfoils, but regardless this fact, it stills produce reasonable values of average thrust coefficient and positive average lift coefficient.

In chapter 8, we extended the two-dimensional results presented in chapter 7 to three-dimensional rigid finite-span flapping wings. In this study, we investigated the aerodynamic forces and wake topology behind low aspect ratio flapping wings and their dependence on the Strouhal number and flapping parameters; we also established the best criteria for vortex identification. The simulations show that the wake of thrust producing, rigid finite-span flapping wings is formed by two sets of interconnected vortex ring loops that slowly convert into vortex rings as they are convected downstream. It was also observed that the vortex rings are themselves inclined with respect to the free-stream; the angle of inclination of the vortex rings is found to be in the direction of their motion and in the streamwise direction for thrust producing cases, whereas for drag producing configurations the angle of inclination is opposite to the direction of travel of the incoming flow. The presence of thin contrails that link the vortex loops was also observed; these structures are segments of the wing-tip vortices and, as the vortex loops are convected downstream, these contrails become weaker and ultimately disappear. It was also observed that the wake topology of drag producing flapping wings, in fact, is very different from that of a thrust producing flapping wing; the main differences are the absence of vortex rings and the compactness of the wake. In general, the observed structures are qualitatively similar to those observed in the experiments of Parker *et al.* [138].

The effect of the wing aspect ratio AR on the aerodynamic forces of finite-span wings was also assessed. It was found that as we increase the wing AR, the aerodynamic forces also increase and this is chiefly due to the large area of high aspect ratio wings and to the relatively minor effect of three-dimensionality in long wings. This observation lead us to think that the assumption of two-dimensionality has some validity for birds and insects, where the wings of many species tend to have relatively large aspect ratio.

Finally, besides the heaving and coupled heaving-and-pitching motions, we also studied the root-flapping motion characteristic of some flying animals, a configuration that still remains almost unexplored. From the results obtained, it was found that root-flapping motion produces wake structures very similar to those of heaving or coupled heaving-and-pitching motions, but with the difference that the latter motions generate larger vortices and forces than root-flapping motion, presumably because the average velocity is higher across the span; otherwise the same wake regimes occurs at similar Strouhal numbers.

From a computational point of view, the biggest breakthrough contribution is the proposed gridding methodology, which allows us to efficiently handle single and multiple fixed or moving/deforming bodies in two and three space dimensions. The overlapping grids method, added to the accurate and stable numerical method used to numerically solve the incompressible Navier-Stokes equations and to the numerical tools implemented, constitutes a very powerful tool to solve fluid dynamics problems with fixed or moving/deforming boundaries in two and three space dimensions.

9.2 Perspectives for future work

There are a number of ways in which the current work could be extended and improved. Firstly, the large number of flapping parameters to be considered, even for simple two-dimensional kinematics (such as heaving frequency and amplitude, pitching frequency and amplitude, phase between pitching and heaving, pivot point location, airfoil geometry and so on) and the significant effect each can have on the observed aerodynamic performance, suggest the use of an automated optimization strategy such as gradient-descent based optimization methods or genetic algorithms. Also, the majority of the simulations were performed at low Reynolds number ($Re < 2000$), the extension of the current work to the higher Reynolds numbers characteristic of large birds and high speed fishes and cetaceans is an area of future research.

The fully parallelization of the moving grids solver using the MPI standard remains an open issue. For the moment the moving grids solver was parallelized using the OpenMP API specification, which, while being the easiest way to parallelize a code, is highly limited to the number of processors available per computing node. In general, we used computing nodes with 4 processors, which provided us with a modest speedup of about 1.6 times. The full parallelization of the moving grids solver using the MPI specification will allow us to run the solver on large computing clusters; therefore, we should be able to scale the problems and expect to achieve higher speedups.

Always related to the solver, is the use of multigrid algorithms to solve the pressure equation. During the development and implementation of the numerical tools used, we tested a multigrid solver and the speed-up obtained was remarkably good (about 10 times faster than the serial code), but we found several constrains when using geometries with sharp edges or several patches. These constrains were mainly related to the interpolation between the component grids in the overlapping grid system. Hence, the tune-up of the multigrid solver and the solution of the interpolation issues when coarsening the grid during the multigrid algorithm, is a very promising area where much work has to be done.

Finally, three-dimensional numerical simulations were performed in this dissertation, but a large qualitative and quantitative scale survey as that performed for the two-dimensional case remains to be accomplished and, to the author's knowledge, such as extensive study has not yet been conducted.