Chapter 1

Introduction

1.1 Overview

Biologists, naturalists and bioengineers, all agree that nature relies on reciprocating motions for locomotion and propulsion on land, in the air and sea. Legs for walking, flapping wings for flight and oscillating fins and tails for swimming [4, 21]. Tens, even hundreds of millions of years of evolution have led to the refined forms and motions we see today in birds, insects, fishes, sharks and cetaceans. Biologists, aerodynamicists, engineers and the general public, look on with wonder at the ease with which these creatures stay aloft, propel themselves, navigate and manoeuvre.

Over a million different species of insects fly with flapping wings, and of the living 13000 warm-blooded vertebrate species (*i.e.*, birds and mammals), 10000 types of birds and bats flap their wings to generate propulsion in the skies [165, 167]. Flapping wings for flying and oscillating fins for swimming stand out as one of the most complex yet widespread propulsion methods found in nature. Although aeronautical technology has advanced rapidly over the past 100 years, natural flyers, which have evolved over millions of years, are still impressive and represent one of nature's finest locomotion experiments. Considering that humans move at top speeds of about 5 body lengths per second, a race horse runs approximately 7 body lengths per second, a cheetah accomplishes 18 body lengths per second, a wide body commercial aircraft such as the Boeing 747 flying at top speed (910 kph) achieves 3.6 body lengths per second, a supersonic military aircraft such as the SR-71, traveling near Mach 3 covers about 32 body lengths per second or as the supersonic commercial aircraft, *"Concorde"*, flying at maximum cruise speed (Mach 2.0) only reaches about 10 body lengths per second; it is amazing that a common pigeon frequently attains speeds of 80 kph, which converts to 75 body lengths per second, a starling can travel at 120 body lengths per second, a swan can reach 23 body lengths per second, the desert locust travels at 180 body lengths per second and a common house fly, flying at 3 meters per second can travel 430 body lengths per second [3, 21, 156]. The roll rate of highly aerobatic aircrafts (*e.g.*, the MXS single place aerobatic airplane) is approximately 420 degrees per second, and a barn swallow has a roll rate in excess of 5000 degrees per second [167]. The maximum positive G forces permitted in most general aviation aircrafts is about 4 to 5 G's, select military aircrafts can withstand 8 to 10 G's and high performance aerobatic aircrafts support up to 14 G's. However, many birds routinely experience positive G forces in excess of 10 G's and up to 14 G's [156, 165, 167]. The primary reasons for such superior maneuvering and flight characteristics include the scaling laws (such as low stall velocity, low inertia and low weight) with respect to man-made vehicle's size, as well as intuitive but highly developed sensing, navigation and control capabilities. Quoting McMasters and Henderson [119]: *"Humans fly commercially or recreationally, but animals fly professionally"*.

To gain the benefit of that evolutionary refinement, nature may serve as the inspiration for novel techniques (in human terms) to enhance or supplant traditional sources of propulsion (propellers in ships and submersibles, jet engines and propellers in aircrafts and rotors in helicopters) and lift generation mechanisms (fixed wings and helicopter rotors) in man-made vehicles.

Recently, the engineering community (particularly the aerospace field) has seen renewed interest in the low Reynolds number aerodynamics of flapping wings and hydrodynamics of oscillating fins, and this is chiefly due to the growing interest of developing Micro-Air-Vehicles (MAVs), Autonomous-Underwater-Vehicles (AUVs) and more recently, Nano-Air-Vehicles (NAVs) [43]. These vehicles may use or take advantage of such unconventional propulsion and lift generation methods, in order to achieve better performances than traditional methods.

MAVs are flying vehicles with a maximal dimension of 15 cm or less (which is comparable to the size of small birds or bats), and capable of reaching flight speeds around 10 to 20 meters per second [127]. These vehicles can perform surveillance and reconnaissance missions, sensing at remote or hazardous locations, traffic monitoring, forestry and wildlife surveys, inspection of power lines and aerial photography, among other tasks [120]. MAVs experience the same low Reynolds number as their biological counterparts (typically in the order of 10^3 to 10^5); in this regime fixed wings drop dramatically in aerodynamic performance. At these low Reynolds number values, the fluid flow is prone to separation, resulting in increased drag and loss of efficiency. Even without flow separation, the low Reynolds number results in low lift-to-drag ratio due to the thickness of the boundary layer. It becomes clear that, in order to develop practical MAVs, new ways of generating lift and thrust must be investigated with the aim of overcoming the drawbacks of fixed wings at low Reynolds number.

Both fixed and flapping wings have been explored in the development of MAV vehicles [127]. Fixed wings, turbines and propellers become less efficient as the size and speed of the vehicle (and hence the Reynolds number) decrease. Viscous drag increases due to relatively thicker boundary layer, and flow separation causes loss of lift and increased pressure drag. With the intention of overcoming the problems of fixed wings at low Reynolds number, flapping wings are being actively studied with the hope that they might provide better performance at this flight regime [165]. The use of flapping wings as an alternative to fixed wings is motivated by the observation of the flight of birds and insects, which use flapping wings not only to overcome the difficulties of low Reynolds number, but to exploit the associated aerodynamic phenomena. Traditional aircraft design using fixed wings attempts to ensure that flow stays attached to the airfoil (unstalled) at all times. In contrast, flapping wings rely on vortex separation from the trailing and leading edges of the wings, forming in this way low pressure regions that may be used to create higher lift and thrust than is possible with fixed wings [44, 46].

Several researchers [7, 136, 152, 166, 182, 191, 193, 207], have found that flying and swimming animals cruise at Strouhal numbers (St) corresponding to a regime of vortex growth and shedding in which the propulsion peaks it maximum efficiency. The St is a dimensionless parameter that describes the wing (or tail) kinematics of flying (or swimming) animals and is defined as $St = fA/U$ (where f is the flapping frequency, A the peak to peak amplitude of the flapping stroke and U is the forward velocity). Because natural selection is likely to tune animals for high propulsive efficiency, we expect it to constraint the range of St that natural swimmers and flyers use. Triantafyllou *et al.* [191, 193], Anderson *et al.* [7] and Read *et al.* [152], found that most of the fast swimming fishes oscillate their tails with $0.2 < St < 0.4$, regardless of the size. Wang [207], Taylor *et al.* [182] and Nudds *et al.* [136], also observed that flying animals, converge on the same narrow range of St for cruise conditions (see figure 1.1). In this range, the propulsive efficiency (defined as the ratio of aerodynamic power output to mechanical power input) can be as high as 70% [182]. Optimal St depends subtly on kinematic parameters including angle of attack, amplitude-to-chord ratio, airfoil section, beating frequency and phase of motion.

Hence, it becomes evident that gaining a better understanding of the relationships between the forces produced and the flapping parameters, including St, and the wing motions driving the leading and trailing edge vortex separation, the manner in which the vortices interact with the airfoil and themselves, how they contribute to lift and propulsion and how to optimize the process, would aid in better understanding the propulsion mechanism of birds, insects and fishes for the design of lighter, more efficient and more maneuverable new generation of MAVs or similar applications.

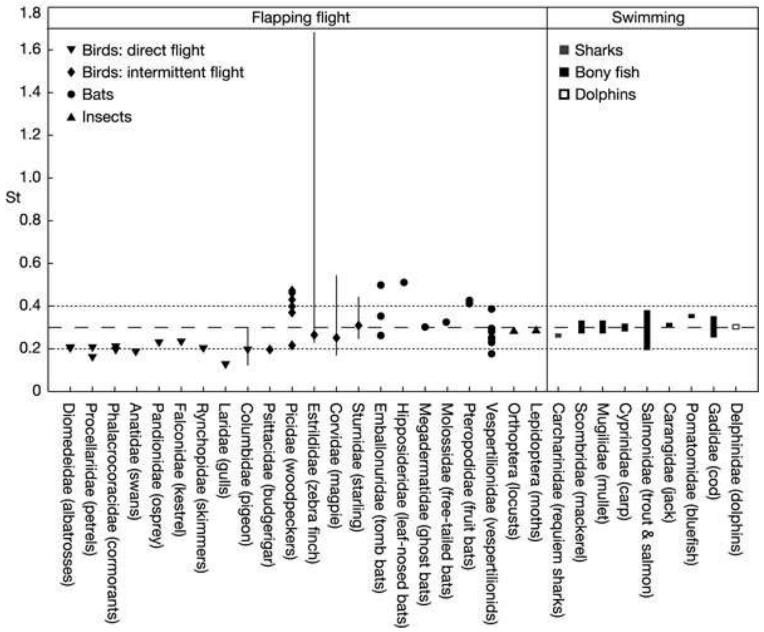

Figure 1.1: *Published ranges (taken from [182]) of St for cruising birds, bats, fishes, sharks and dolphins. Dotted lines mark the range* $0.2 < St < 0.4$, *in which propulsive efficiency usually peaks; dashed line marks the modal peak at* $St = 0.3$. *Unbroken lines indicate the range of variation in St across other non-zero flight speeds, where such data exist.*

Apart from the biomechanical design aspects, further motivation may be found in understanding the aerodynamics and hydrodynamics of natural flyers and swimmers. These areas of research include:

- The unsteady aerodynamics of helicopter rotor blades undergoing cyclical flapping motions.

- Flow control and flow reattachment through shape control.
- Blade-vortex interaction for noise prevention in rotorcrafts.
- Interaction and decay of vortex wakes to minimize hazards to aircrafts.
- Fluid-structure interactions and aerodynamic flutter.
- Wake vortex dynamics.

This dissertation investigates the aerodynamics of low Reynolds number flapping airfoils/wings, from the perspective of efficient thrust generation and propulsion efficiency (whether for better understanding the aerodynamics of natural flyers, the hydrodynamics of natural swimmers, or for MAV/AUV applications). It mainly deals with the aerodynamics of two-dimensional flapping rigid and flexible/deforming airfoils (as many of the phenomena of interest such as; thrust generation, inversion of the vortex street and leading edge vortex separation, can be captured with two-dimensional simulations), and to a lesser extent with the aerodynamics of three-dimensional flapping rigid wings. This limitation is mainly due to the unsteady nature of the flow and the requirement for high resolution in regions of flow separation, vortex shedding and vortex wake evolution, which added to the requirement of bigger and finer computational domains for three-dimensional simulations, would create an impractical computational load given the current resources available. As noted by Wang [207], *"a two-dimensional computation can serve both as a reliable tool in its own right and a useful reference point to be compared with three dimensional simulations"*.

The current work is fully based on numerical simulations. The governing equations of fluid dynamics and the highly unsteady aerodynamics of the flapping motion are solved using a Navier-Stokes flow solver on overlapping grids. The use of unsteady potential methods [86, 93, 94, 177, 183, 212] is not consider, this is chiefly due to the limitations imposed by these methods of assuming inviscid flow and flow separation only from the trailing edge of the airfoil (as imposed by the Kutta condition in potential methods), hence better resolution and representation of the flow physics is obtained by using Navier-Stokes solvers, but with the drawback of being more time consuming and computational expensive. Finally, the obtained results are interpreted and analyzed and where is possible, are compared against other experimental and computational results found in the literature in order to explain the observed phenomena and to characterize the parameters governing the mechanism of flapping wings propulsion, in terms of thrust production and propulsive efficiency.

1.2 Objectives

The objectives of this dissertation are, from the biomechanical point of view of flapping wings propulsion:

- the study of the mechanisms of thrust generation by flapping airfoils/wings at low Reynolds number, in the range typical of birds, large insects and potential MAV, NAV and UAV in order to:
  - explain the experimentally and numerically observed wake structures for flapping airfoils;

  - determine the relationships between thrust production and propulsive efficiency, wake structure, wing geometry and flapping parameters such as frequency, amplitude of motion (maximum heaving and pitching amplitude) and phase angle;

- compare the performance parameters and wake structures of the flapping motion of rigid and flexible/deforming airfoils;

- determine the relative importance of leading and trailing edge vortex shedding in the generation of the wake structures and aerodynamics forces;

- to examine the validity of a single parameter (Strouhal number), as the fundamental aerodynamic parameter insofar as high propulsive efficiency is concerned;

and from the computational point of view:

- to propose the best methodology to efficiently handle moving and deforming bodies;

- to compute efficient solutions in terms of problem definition (geometry, kinematics, Reynolds number, Strouhal number and so on) and computing time.

1.3 Outline of the dissertation

In order to meet the objectives stated above, this dissertation is divided into nine chapters. In chapter 1, a short introduction and an outline of the objectives of this dissertation are given.

In chapter 2, a literature review on the aerodynamics of low Reynolds number flapping airfoils is presented. This covers their use in nature, some experimental observations, various analytical and numerical techniques, a review of nonstationary airfoil aerodynamics including dynamic stall, vortex shedding and thrust generation, a presentation of flapping flight in terms of Reynolds number, Strouhal number and reduced frequency and a discussion of flapping wings performance parameters and flapping wings kinematics.

Chapter 3, presents the governing equations of fluid dynamics and their nondimensionalization; followed by a description of their transformation to generalized curvilinear coordinates and a presentation of the governing equations for the case of an incompressible viscous flow.

In chapter 4, the structured overlapping grids method is reviewed and discussed in the context of a method for the efficient solution of the governing equations around complex geometries and moving/deforming bodies.

Chapter 5, describes the numerical method used to solve the governing equations on overlapping grids. The numerical method presented is a split-step scheme, second-order accurate in space and time and solves the momentum equations for the velocity together to a Poisson equation for the pressure (the so called pressure-Poisson equation or PPE), this system of equations is known as the velocity-pressure formulation of the incompressible Navier-Stokes equations.

In Chapter 6, a qualitative and quantitative validation and verification of the proposed computational tool against experimental and numerical results is carried out in order to assess its numerical accuracy. Also in this chapter, a grid dependency study is conducted in order to determine the best suited grid for the computations to be performed in the next chapter.

In chapter 7, we present several two dimensional results for heaving and coupled heaving-and-pitching motions. The interest here is to determine the values of flapping frequency and flapping amplitude best suited for flapping flight, in terms of maximum efficiency and thrust production. We also study the influence of airfoil cambering and airfoil flexibility on lift and thrust generation.

In chapter 8, we extend the two-dimensional results presented in chapter 7 to three-dimensional rigid finite-span flapping wings. In this chapter, we investigate the wake topology behind low aspect ratio flapping wings and their dependence on the Strouhal number and flapping parameters. We also present some results on the aerodynamic performance of flapping wings, as well as we establish the best criteria for vortical structures identification.

Finally, we conclude by presenting the major conclusion and future perspectives in Chapter 9.