CHAPTER ONE

Introduction

Bird, bat, and insect flight has fascinated humans for many centuries. As enthusiastically observed by Dial (1994), most species of animals fly. There are nearly a million species of flying insects, and of the living 13,000 warm-blooded vertebrate species (i.e., birds and mammals), 10,000 (9000 birds and 1000 bats) have taken to the skies. With respect to maneuvering a body efficiently through space, birds represent one of nature's finest locomotion experiments. Although aeronautical technology has advanced rapidly over the past 100 years, nature's flying machines, which have evolved over 150 million years, are still impressive. Considering that humans move at top speeds of 3–4 body lengths per second, a race horse runs approximately 7 body lengths per second, a cheetah accomplishes 18 body lengths per second (Norberg, 1990), a supersonic aircraft such as the SR-71, "Blackbird," traveling near Mach 3 (~2000 mph) covers about 32 body lengths per second, it is amazing that a common pigeon (*Columba livia*) frequently attains speeds of 50 mph, which converts to 75 body lengths per second. A European starling (*Sturnus vulgaris*) is capable of flying at 120 body lengths per second, and various species of swifts are even more impressive, over 140 body lengths per second. The roll rate of highly aerobatic aircraft (e.g., the A-4 Skyhawk) is approximately 720°/s, and a Barn Swallow (*Hirundo rustics*) has a roll rate in excess of 5000°/s. The maximum positive G-forces permitted in most general aviation aircraft is 4–5 G and select military aircraft withstand 8–10 G. However, many birds routinely experience positive G-forces in excess of 10 G and up to 14 G. The primary reasons for such superior maneuvering and flight characteristics include the "scaling laws" with respect to a vehicle's size, as well as intuitive but highly developed sensing, navigation, and control capabilities. As McMasters and Henderson put it, humans fly commercially or recreationally, but animals fly professionally (McMasters and Henderson, 1980). Figure 1.1 illustrates several maneuvering characteristics of biological flyers; these capabilities are difficult to mimic by manmade machines. Combining flapping patterns, body contour, and tail adjustment, natural flyers can track target precisely and instantaneously. Figure 1.2 shows hummingbirds conducting highly difficult and precise flight control. To take off, natural flyers synchronize wings, body, legs, and tail. As shown in Figure 1.3, they can take off on water, from land, and off a tree, exhibiting varied and sophisticated patterns. While gliding, as shown in Figure 1.4, they flex their wings to control their speed as well as the direction. On landing, as depicted in Figure 1.5, birds fold their wings to reduce lift, and flap to accommodate wind gusts and to adjust for the location of the available landing area.

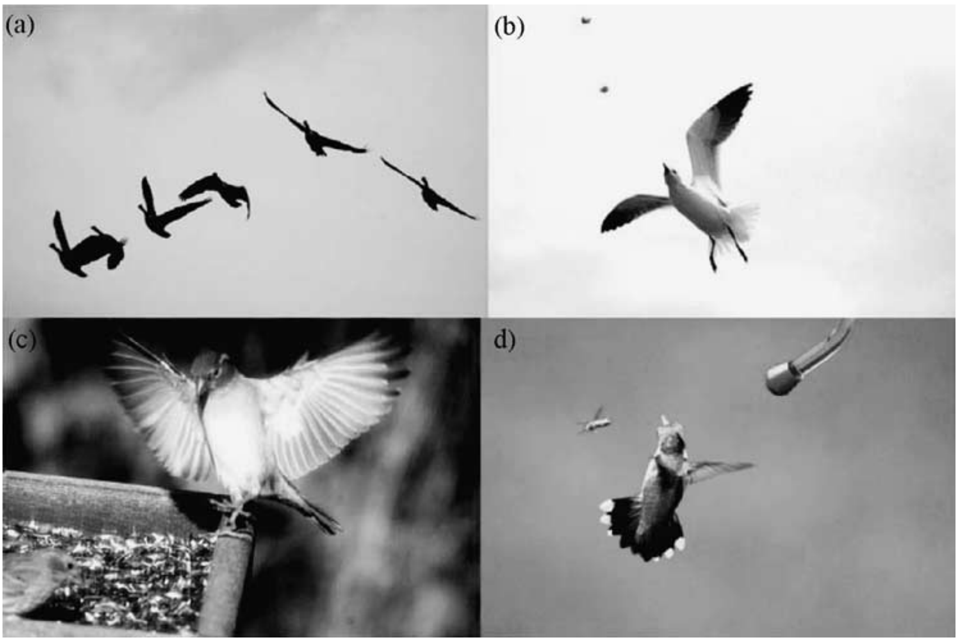

Figure 1.1. Maneuvering capabilities of natural flyers: (a) Canadian geese's response to wind gust; (b) speed control and target tracking of a seagull; (c) precision touchdown of a finch; (d) a hummingbird defending itself against a bee.
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Figure 1.2. Natural flyers can track target precisely and instantaneously. Shown here are hummingbirds using flapping wings, contoured body, and tail adjustment to conduct flight control.
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Wei Shyy, Yongsheng Lian, Jian Tang, Dragos Viieru and Hao Liu
Excerpt
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Figure 1.3. Natural flyers synchronize wings, body, legs, and tail to take off (top) on water, (middle) from land, and (bottom) off a tree.
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Since the late 1990s, the so-called micro air vehicles (MAVs) have attracted substantial and growing interest in the engineering and science communities. The MAV was originally defined as a vehicle with a maximal dimension of 15 cm or less, which is comparable to the size of small birds or bats, and a flight speed of 10–20 m/s (McMichael and Francis, 1997). Equipped with a video camera or a sensor, these

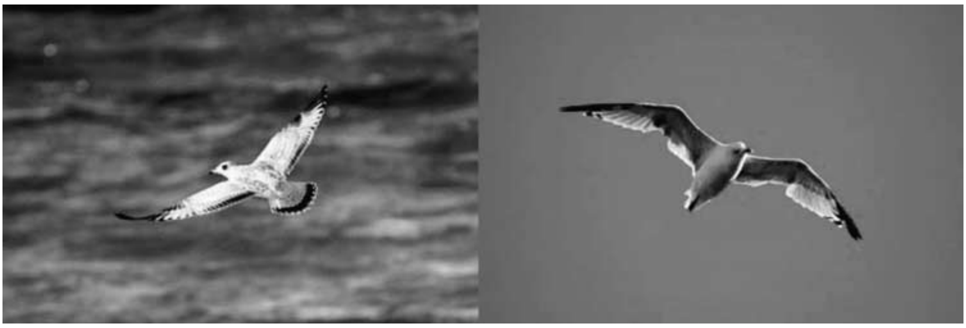

Figure 1.4. Birds such as seagulls glide while flexing their wings to adjust their speed as well as to control their direction.
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Figure 1.5. On landing, birds fold their wings to reduce lift, and flap to accommodate wind gusts and to adjust for their available landing area.
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vehicles can perform surveillance and reconnaissance, targeting, and biochemical sensing at remote or otherwise hazardous locations. With the rapid progress made in structural and material technologies, miniaturization of power plants, communication, visualization, and control devices, numerous groups have developed successful MAVs. Overall, alternative MAV concepts, based on fixed wing, rotary wing, and flapping wing, have been investigated. Figure 1.6(a) shows a 15-cm MAV designed by Ifju et al. (2002), which uses a fixed, flexible-wing concept. Figure 1.6(b) shows a rotary-wing MAV with 8.5-cm rotary diameter designed by Muren (http://www.proxflyer.com). Figure 1.6(c) shows a biplane MAV designed by Jones and Platzer (2006), which uses a hybrid flapping–fixed-wing-design, with the flapping wing generating thrust and the fixed wing producing necessary lift. Figure 1.6(d) shows a recent development by Kawamura et al. (2006) that relies on flapping wing to generate both lift and thrust and possesses some flight control capabilities.

Figure 1.7 highlights more detailed vehicle characteristics of flexible-wing MAVs designed by Ifju and coworkers. The annual International Micro Air Vehicle

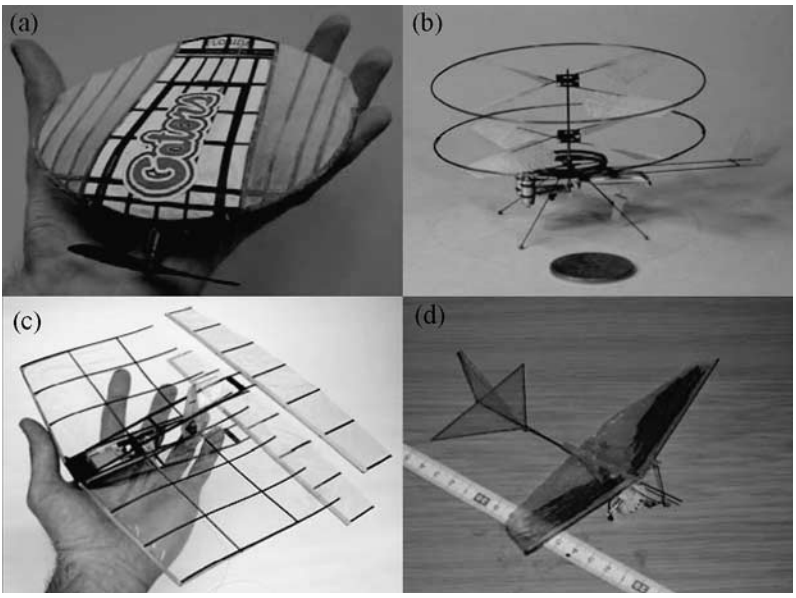

Figure 1.6. Representative MAVs: (a) flexible fixed wing (Ifju et al., 2002); (b) rotary wing (http://www.proxflyer.com); (c) hybrid flapping–fixed wing, with the fixed wing used for lift and the flapping wing for thrust (Jones and Platzer, 2006); and (d) flapping wing for both lift and thrust (Kawamura et al., 2006).
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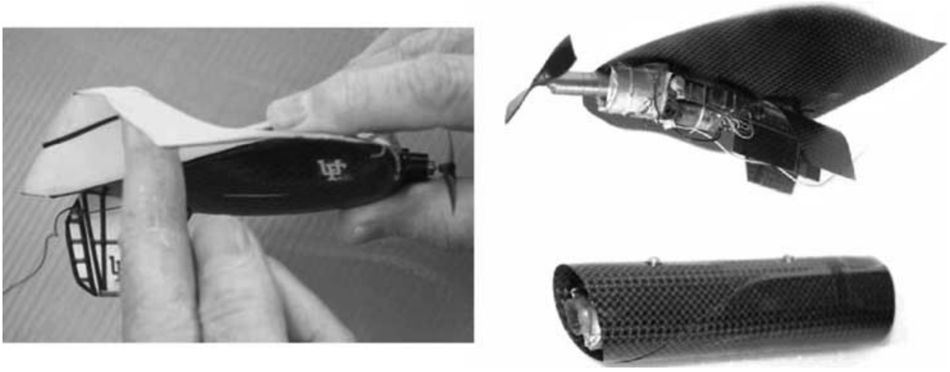
Competition has offered a substantial forum, encouraging the development of MAVs. For example, one of the competition categories is to fly 600 m, capture an image of a 1.5 m × 1.5 m target, and transmit the image with telemetry. The smallest vehicle capable of successfully completing the mission is declared the winner. Since the first competition, the winning vehicle's size has drastically decreased, and now the maximum dimension is just barely over 10 cm.

The MAVs operate in the low Reynolds number regime (originally envisioned to be 10^4–10^5, now even lower), which, compared with large, manned flight



(a) (b)

Figure 1.7. The flexible-wing MAVs (a) can benefit from passive shape adaptation in accordance with instantaneous aerodynamic loading, and (b) can be packed very easily based on need (courtesy Peter Ifju).

vehicles, have unfavorable aerodynamic characteristics, such as low lift-to-drag ratio (Lissaman, 1983). On the other hand, the MAVs' small geometric dimensions result in favorable scaling characteristics, such as reduced stall speed and better structural survivability.

There is great potential for collaborative research between biologists and engineers because MAVs and biological flyers share similar dimensions, weight, flight speeds, and flight environment. Substantial literature exists, especially in the biological community. General references offering broad accounts of biological flight, including geometric scaling laws, power, and morphology, as well as simplified modeling, can be found in Alexander (2002), Azuma (1983), Biewener (2003), Brodsky (1994), Dudley (2000), Grodnitsky (1999), Norberg (1990), Tennekes (1996), Videler et al. (2004), Vogel (1996), and Ward-Smith (1984). The symposia volumes edited by Wu et al. (1975), Pedley (1977), and Maddock et al. (1994) offer multiple angles related to flight as well as to swimming. Lighthill (1969, 1977), Wu (1971), Childress (1981), and Maxworthy (1979) discuss swimming and flying primarily from analytical viewpoints. Finally, the standard texts by Anderson (1989), Katz and Plotkin (2002), and Shevell (1983) present basic knowledge related to the aerodynamics of airplane flight. Our effort in this book is aimed at the aerodynamics relevant to both biological flyers and manmade MAVs.

In this chapter, we first introduce the flapping flight in nature, including the kinematics of flapping-wing vehicles and the lift- and thrust-generation mechanisms. Second, we present the scaling laws related to the mechanics and energetics of avian flight. Then we discuss drag and power related to avian flight. These two quantities are intimately connected. The different power components are presented separately and later summed together, giving the total power required for hovering and forward flight. A comparison between the power components for a fixed- and a flapping-wing vehicle is also presented. The results of these different power calculations are summarized in the form of power curves.

1.1 Flapping Flight in Nature

Flapping flight is more complicated than flight with fixed wings because of the structural movement and the resulting unsteady fluid dynamics. Conventional airplanes with fixed wings are, in comparison, very simple. The forward motion relative to the air causes the wings to produce lift. However, in biological flight the wings not only move forward relative to the air, they also flap up and down, plunge, and sweep (Dial, 1994; Goslow et al., 1990; Norberg, 1990; Shipman, 1998; Tobalske and Dial, 1996). Early photographs and some general observations are given by Aymar (1935) and Storer (1948).

While flapping, birds systematically twist their wings to produce aerodynamic effects in ways that the ailerons on the wings of conventional airplanes operate. Specifically, one wing is twisted downward (pronated), thus reducing the angle of attack (AoA) and corresponding lift, while the other wing is twisted upward (supinated) to increase lift. With different degrees of twisting between wings, a bird

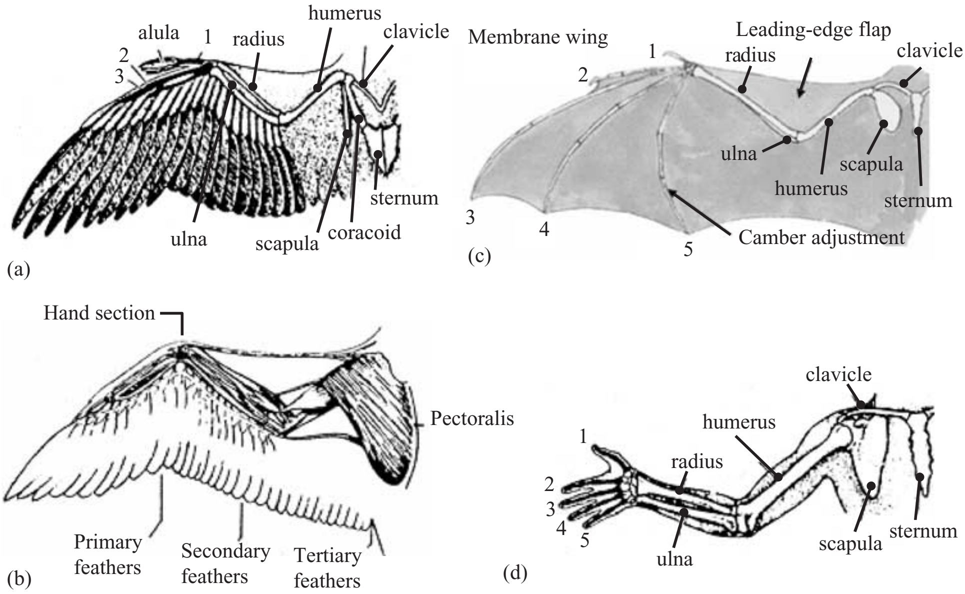


Figure 1.8. Schematics of (a), (b) a bird wing, (c) a bat wing, and (d) a human arm. For birds, the upper arm, the "humerus," is proportionately shorter, the "wrist" and "palm" bones are fused together for greater strength in supporting the primary flight feathers. For bats, the bone–membrane combination creates a leading-edge flap and allows passive camber adaptation in the membrane area. (a), (b), and (d) are modified from Dhawan (1991); (c) is adopted from Anders (2000).

is able to roll (Dial, 1994). For a bird to be able to deform and twist its wings, an adaptation in the skeletal and muscular systems is required. The key features that seem desirable are modification of camber and flexing of the wing planform between upstroke and downstroke, twisting, area expansion and contraction, and transverse bending. To perform these functions, birds have a bone structure in their wings similar to the one in a human arm. However, birds have more stringent muscle and bone movement during flight. Figure 1.8 shows a schematic of a bird wing compared with a human arm and hand. Figure 1.9 compares the cross-sectional shapes of a pigeon wing and a conventional transport airplane wing. The pigeon wing exhibits noticeably more variations in camber and thickness along the spanwise direction.

1.1.1 *Unpowered Flight: Gliding and Soaring*

Flying animals usually flap their wings to generate both lift and thrust. But if they stop flapping and keep their wings stretched out, their wings actively produce only lift, not thrust. Thrust can be produced by gravity force while the animal is descending. When this happens, we call them gliders. In addition to bats and larger birds, gliders can also be found among fish, amphibians, reptiles, and mammals.

To maintain level flight, a flying animal must produce both lift and thrust to balance the gravity force in the vertical direction and drag in the horizontal

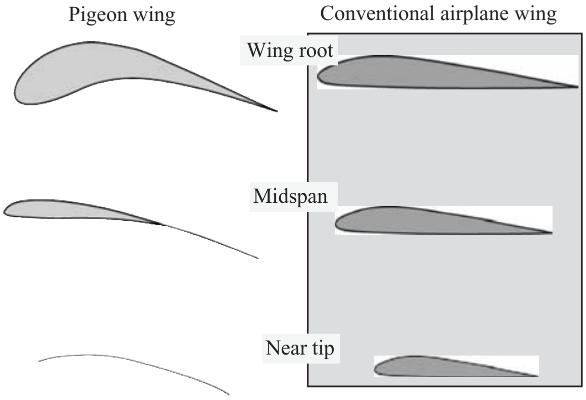


Figure 1.9. Comparison of cross-sectional shapes of a pigeon wing and a conventional transport airplane wing. The pigeon wing exhibits noticeably more variations in camber and thickness along the spanwise direction.

direction, respectively. Because gliding occurs with no active thrust production, an animal always resorts to the gravity force to overcome the drag. In gliding, the animal tilts its direction of motion slightly downward relative to the air that it moves through. When the animal tilts downward, the resulting angle between the motion direction and the air becomes the gliding angle. The gliding angle directly controls the lift-to-drag ratio. The higher this ratio, the shallower the glide becomes. Recall from basic fluid dynamics that the lift-to-drag ratio increases with the Reynolds number, a parameter proportional to animal size and flight speed. Large flying animals fly at high Reynolds numbers and have a large lift-to-drag ratio. For example, a wandering albatross, with a wing span of over 3 m, has a reported lift-to-drag ratio of 19 whereas the fruit fly, which has a span of 6 mm, has a ratio of 1.8 (Alexander, 2002). If the animal has a low lift-to-drag ratio, it must glide (if it can) with a considerably large glide angle. For example, a lizard in the Southeast Asian genus *Draco* has a lift-to-drag ratio of 1.7 and it glides at an angle of 30°; a North American flying squirrel has a glide angle of about 18°– 26° with a lift-to-drag ratio of 2 or 3 (Alexander, 2002).

While gliding animals take a downward tilt to have the gravity-powered flight, many birds can ascend without flapping their wings, and this is called soaring. Instead of using gravity, soaring uses energy in the atmosphere, such as rising air currents (Alexander, 2002).

1.1.2 *Powered Flight: Flapping*

An alternative method to gliding used by many biological flyers to produce lift is flapping-wing flight. The similarities between the aerodynamics of a flapping wing and that of a rotorcraft, although limited, can illustrate a few key ideas. Take for example the rotors of a helicopter, which rotate about the central shaft continuously. The relative flow around the rotors produces lift. Likewise, a flapping wing

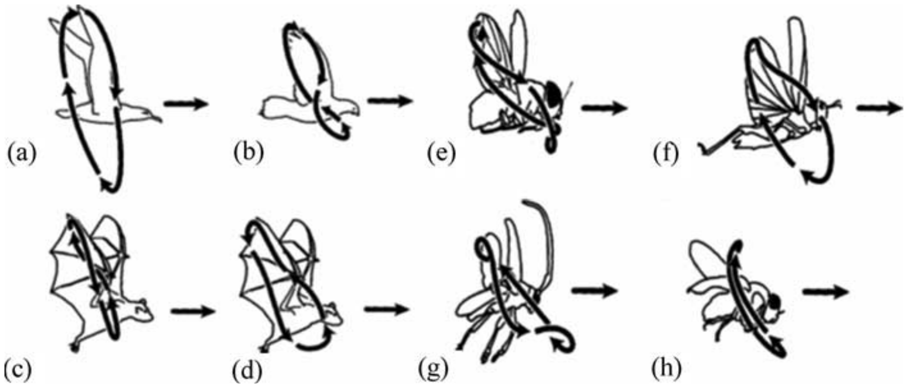


Figure 1.10. Wingtip paths relative to the body for a variety of flyers, as indicated by the arrows: (a) albatross, fast gait; (b) pigeon, slow gait; (c) horseshoe bat, fast flight; (d) horseshoe bat, slow gait; (e) blowfly; (f) locust; (g) June beetle; (h) fruit fly. Adopted from Alexander (2002).

rotates, swings in an arc around its shoulder joint, and reverses direction every half-stroke. Helicopters and biological flyers use similar techniques to accelerate from hovering to forward flight as well. Helicopters tilt the rotational plane of rotors from horizontal to forward. The steeper the tilt of the rotor, the faster the helicopters accelerate. Biological flyers also tilt their flapping stroke plane: down and forward on the downstroke, and up and backward on the upstroke. To fly faster, biological flyers make the stroke more vertical by increasing the up-and-down amptitude of the movements. When biological flyers decrease their speed, they tend to flap their wings more horizontally, similar to the way helicopters change their rotors.

Birds, bats, and insects apply a variety of different flapping patterns in hovering and forward flight to generate lift and thrust. Larger birds have relatively simple wingtip paths. For example, an oval tip path is often associated with albatrosses (see Figure 1.10). Smaller flyers exhibit more complicated flapping patterns. Figure 1.10 illustrates the highly curved tip paths of a locust and a fruit fly, the figure-eight pattern of a pigeon, and the more complicated paths of June beetles and blowflies.

1.1.3 *Hovering*

Whether a flying animal can hover or not depends on its size, moment of inertia of the wings, degrees of freedom in the movement of the wings, and the wing shape. As a result of these limitations, hovering is mainly performed by smaller birds and insects. Larger birds can hover only briefly. Although some larger birds like kestrels seem to hover more regularly, in fact, they use the incoming wind to generate enough lift. There are two kinds of hovering, symmetric hovering and asymmetric hovering, as described by Weis-Fogh (1973) and Norberg (1990).

Figure 1.11. Selected seagull wing configurations during flapping, which show various stages of strokes. Note that the wings are often flexed with their primaries rotated.

For larger birds, which cannot rotate their wings between forward and backward strokes, the wings are extended to provide more lift during downstroke, whereas during the upstroke the wings are flexed backward to reduce drag. In general the flex is more pronounced in the slow forward flight than in fast forward flight. This type of asymmetric hovering is usually called "avian stroke" (Azuma, 1992) and is illustrated in Figure 1.11. As shown in the figure, to avoid large drag forces and negative lift forces, these birds flex their wings during the upstroke by rotating the primaries (tip feathers) to let air through.

Symmetric hovering, also called normal or true hovering, or "insect stroke," is performed by hummingbirds or insects that hover with fully extended wings during the entire wing-beat cycle. Lift is produced during the entire wing stroke, except at the reversal points. The wings are rotated and twisted during the backstroke so that the leading edge of the wing remains the same throughout the cycle, but the upper surface of the wing during the forward stroke becomes the lower surface during the backward stroke. The wing movements during downstroke and upstroke can be seen in Figure 1.12. Note that, during hovering, the body axis is inclined at a desirable angle and the wing movements describe a figure of a lying eight in the vertical plane.

1.1.4 *Forward Flight*

When a natural flyer's aerodynamic performance is analyzed, an important parameter is the ratio between the forward velocity and the flapping velocity, which is expressed in terms of the reduced frequency:

$$k = \frac{\omega c}{2U_{\mathrm{ref}}}, \qquad (1.1)$$

where ω, c, and U_{ref} are, respectively, the angular velocity of a flapping wing, the wing's reference chord, and the reference velocity, in this case the flyer's forward-flight velocity. The unsteady effects increase with increasing reduced frequency, and