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Abstract

Biologic flight has undoubtedly intrigued man for thousands of years, yet it has been only the last 100 years or so that any serious challenge has been mounted to the pre-eminence of birds. Although present-day large-scale aircraft are now clearly able to fly higher, faster and farther than any bird or insect, it is obvious that these biological creatures have a mastery of low Reynolds number, unsteady flows that is unrivaled by man-made systems. This paper suggests that biological flight should be examined for mechanisms that may apply to engineered flight systems, especially in the emerging field of small-scale, uninhabited aerial vehicles (UAV). This paper discusses the kinematics and aerodynamics of bird and insect flight, including some aspects of unsteady aerodynamics. The dynamics of flapping wing flight is briefly examined, including gait selection, flapping frequency and amplitude selection, as well as wing planform and angle-of-attack dynamics. Unsteady aerodynamic mechanisms as practiced by small birds and insects are reviewed. Drag reduction morphologies of birds and marine animals are discussed and fruitful areas of research are suggested.

Introduction

Early attempts at manned flight relied on designs mainly copied from nature. These designs were gleaned from long hours observing birds that seemed to glide effortlessly on invisible air currents. Octave Chanute, in his book *Progress in Flying Machines*[1], provided an exhaustive review of most of these early experiments,

starting with the designs of Leonardo Da Vinci for a flapping device dating from approximately 1500 AD. These early inventors naturally assumed that feathered, flapping wings could be scaled up to provide a man-sized aircraft. Figures 1 and 2, taken from reference 1 are typical of some of the mid-to-late 19th century designs. The wings in figure 2 are supposedly an exact replication of a crow (multiple wing positions are shown in the drawing). Chanute detailed the
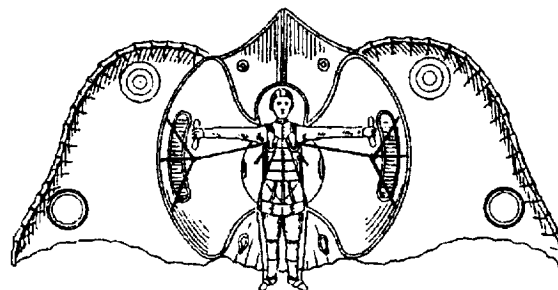

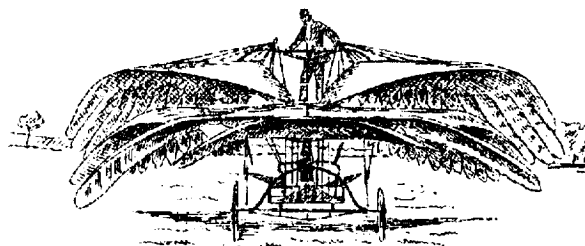**Fig. 1. 1854 design of Breant (from Chanute, ref. 1).**

Fig. 2. 1890 design of Frost (from Chanute, ref. 1)

assumptions used for estimating the power required, and pointed out that in order to flap using muscle power

alone the inventors had to scale down the wings to impossibly small sizes. Wings appropriately-sized for human flight could hardly be flapped at all. Much effort was then expended in an attempt to find a lightweight power plant to replace human muscle power as the energy source. At the same time, some methods of providing a measure of stability and control were sought. Glider experiments by Lilienthal[2] and others showed that this was a non-trivial problem, and that, apparently, birds had buried in their anatomy some sort of sophisticated control system to maintain stability in gusty air. Lilienthal himself remarked on "...how hard it is to maintain a stable equilibrium in the air and to counteract the "whims" of the wind".

Natural flight is no longer used as a guide to designing airplanes, and with our understanding of the laws of aerodynamics and stability and control we have succeeded in building 850,000 pound "birds" that fly near the speed of sound. However, recent concerns about our environment and quality of life (especially near airports) have prompted many to question the global and local effects of aircraft emissions (unburned hydrocarbons, noise, and water vapor), not to mention the sometimes heated controversy over land use that limits new airport construction. The projected increase in air travel over the next decade[3] has heightened awareness that new ideas are urgently needed on ways to increase the efficiency of transport aircraft, or perhaps, on ways of designing revolutionary new aircraft that will have less of an impact on our environment.

Although our engineering designs may exceed nature with regard to size, speed, and range they are inferior to nature in other ways. Nature builds self-assembling systems of staggering complexity, yet these systems provide robust, autonomous, and efficient solutions that are well adapted to the environment. Therefore, some are suggesting[4] that the time has come to reexamine nature, in a way reminiscent of those early aerodynamic pioneers, but with an important difference. That is, can biological systems, with millions of years of evolutionary re-design, offer fresh inspiration for engineering solutions that work better, are more efficient, and at the same time are more environmentally acceptable to future generations?

Natural systems tend to minimize "cost" for maximum "gain" by exploiting a niche in the environment where they can prosper using some unique capability. They also have the capability to adapt as conditions change (within limits), to self-repair (within limits), to cooperate for the good of the group, and to minimize their energy use. It may be that at least some these biological principles can also be applied to engineered systems to minimize cost and maximize gain (function).

As with any review, it is virtually impossible, within the normal constraints of space and time, to cover this field in any great detail. The interested reader is encouraged to pursue the reference list for more in-depth discussions of the various topics. This paper will attempt to outline some of the mechanisms so far identified in biological flight that may have application to engineered flight. The problem of scale will be reviewed briefly, and the steady and unsteady mechanisms of insect and vertebrate flight will be discussed. The specialized morphologies and kinematics used in biological flight (marine and avian), so far as they are known will be discussed. For the most part, common names are used for the various species since Latin names add little information for the non-biologist.

This paper will suggest that one of the key flow control features of biologic flight systems stems from their creation of, and use of, unsteady flows. Unsteady flows are only recently being employed for control purposes (synthetic jets for separation control, for example) and our understanding and computational tools are still somewhat rudimentary. While we are still a long way from building a "designer" bird using unsteady aerodynamics, it is beginning to look reasonable that, with properly engineered aeroelastic materials, integrated sensors, and advanced power supplies, it may be possible to design small-scale vehicles with enhanced agility, adaptability and endurance.

All of the work cited here has been done by others and merely collected by this author. Any errors of interpretation are entirely the fault of the author, and any sins of omission may be blamed on his very brief period of immersion in this fascinating field. Perhaps the ultimate usefulness of this work will be simply to

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stimulate thought by aerodynamicists on novel ways of solving the problems of flight and flow control.

Symbols

AR = aspect ratio

b = wing semi-span

c = mean aerodynamic chord

C_l = lift coefficient

C_d = drag coefficient

D = drag

g = gravitational constant

J = advance ratio

k = reduced frequency parameter (eqn. 5)

K = reduced frequency parameter (eqn. 7)

K_1 = mechanical work per unit of oxidized fuel

L = lift

m = mass

n = wing beat frequency

r = spanwise distance from wing root

Re_c = Reynolds number based on wing chord

U = forward flight speed

W_1 = takeoff weight

W_2 = landing weight

Φ = wing stroke amplitude

ω = circular frequency

Ω = reduced frequency parameter (eqn. 6)

The Case for Flapping Flight

Most living things fly[5,6,7]. There are on the order of 1,000,000 described species of flying insects (with perhaps as many as 10,000,000 yet undescribed[6]) and approximately 10,000 species of birds and bats[7]. One reason most things fly is because it is more economical in terms of energy per unit distance[5]. Obviously, the power requirements are higher than for walking or running, but since flying is generally much faster, the distance traveled per unit time is much greater. The diversity of flight mechanisms devised by nature is truly staggering, and most of this diversity has existed for 200-or-so million years[6]. Figure 3, derived from Grodnitsky[8], shows a classification of insect wing functions that is truly bewildering to the aerodynamicist. Why did nature develop so many different ways of integrating the lift and propulsion

systems of flying insects? Or, perhaps more generally, one might ask "do all these varied airborne biological systems (with their many different ways of flying) represent highly efficient flight systems, or are some of nature's flight solutions better and more efficient than others?"
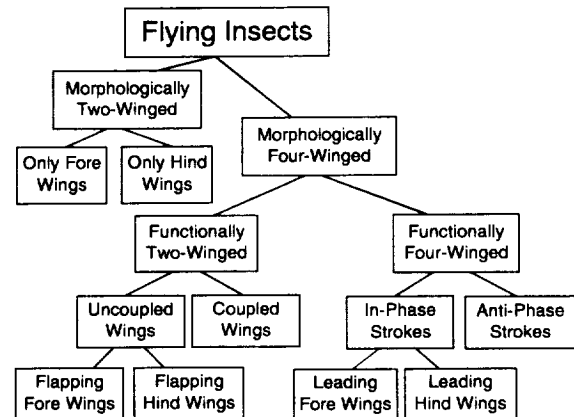
Fig. 3. Classification of wing strokes
(after Grodnitsky, ref. 8)

The scale of the creature obviously has a first order effect on the flight system and, as a result, insects and birds have evolved completely different flapping wing systems (with the exception of the hummingbird which functions aerodynamically more like an insect than a bird). The next section will discuss in a bit more detail the effects of scale. But, among insects, even of the same scale, many different solutions to the flight problem persist. Ward-Smith[9] indicates that the earliest insects, which appeared some 270 million years ago, had two pairs of wings that functioned independently, a system that survives today in dragonflies, cockroaches, grasshoppers, and mayflies. He further states that this system is aerodynamically inefficient, and evolution in many orders resulted in 4-wing systems that function today essentially as two-wing systems. Grodnitsky[8] and Dudley[6] give detailed discussions of insect wing diversity and evolution, but the question remains as to why so many different systems have been retained over millions of years. One answer may be, of course, that insect flight systems are subject to many evolutionary forces beyond simply aerodynamic efficiency. The environment, the food supply, the ability to evade predators, the ability to attract a mate, and the mating process itself all influence the design and evolution of

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the flight system[6]. Also, wings are not only used for flight but provide, in some species, thermal regulation, armor for protection, and a means of communication[6]. That leaves the aerodynamicist in somewhat of a conundrum when trying to deduce which features are important aerodynamically and which features were developed for other purposes. Nature is in the business of cost efficiency[5], however, and one might expect that all these creatures make very efficient use of their energy resources.

The efficiencies achieved by biological systems are sometimes overstated, however, and a simple example may help to illustrate that point. First, the migration patterns of birds has long been observed, but, until lately, poorly documented. A recent popular press book, *Living on the Wind*[10], by Scott Weidensaul provides an entertaining and informative review of bird migration, and some of the conclusions are at first truly staggering. For example, the blackpoll warbler is a half-ounce songbird, which summers in the region from western Alaska to Labrador, but winters as far south as the western Amazon. This tiny bird flies non-stop from the Maritime Provinces across the open Atlantic to a landfall along the coast of Venezuela in a 40-to-50-hour, 2,000 mile marathon, using nothing but a fraction of an ounce of body fat for fuel. Weidensaul jokes that this is the equivalent of 720,000 miles per gallon. A much larger bird, the bar-tailed godwit, migrates from eastern Siberia and western Alaska to New Zealand, a non-stop 4-to-5-day trip of as long as 6,800 miles, making it perhaps the longest, non-stop bird migration in the world. Pennycuick[11] suggests that long-distance migrating birds may be able to store (and lift) as much as 50% body fat when beginning their migration and estimates the distance a bird can fly without refueling as;

$$\text{Range} = K_1/g(L/D)\ln(W_1/W_2) \qquad (1)$$

This equation looks very similar to the range equation for conventional aircraft. Note that for a given fuel fraction $(1-W_2/W_1)$ the range depends only on the L/D ratio, and not on the size of the bird. As mentioned earlier, a small bird can have a fuel fraction of 50% and equation (1) predicts a range of about 3500 miles for an assumed L/D of 10 (see figure 4). Withers[12] found that common bird wings, when tested in the wind tunnel,

have L/D ratios ranging from about 3 for a starling to 17 for a swift. Therefore, an assumed average L/D of 10
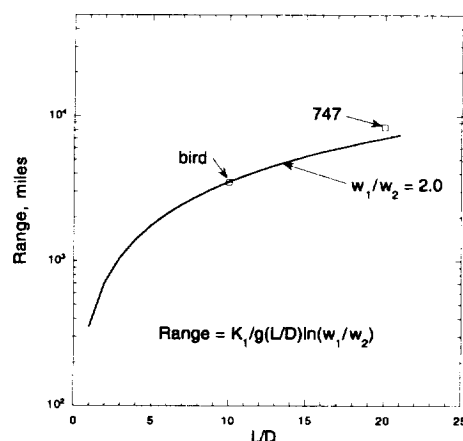

Fig. 4. Simplified range equation

is entirely plausible, and the predicted range is certainly within the limits of what is observed in nature. Larger birds tend to have higher L/D ratios, but can carry smaller loads (fuel ratio) so the end result is that the long distance ability is roughly the same regardless of size[11]. As remarkable as these non-stop migrating flights seem, biological systems are not really performing miracles. The range for a Boeing 747-400, with a maximum takeoff weight of 875,000 pounds (of which, approximately 330,000 pounds is fuel) and a cruise L/D of approximately 20, is about 8,400 miles. Thus, a 747 has twice the L/D and approximately twice the range with a slightly lower fuel fraction (.38). If we ignore, for this simple calculation, the reserve fuel that transport aircraft are required to carry, the above result implies that the efficiency of a bird burning fat and the efficiency of a transport aircraft burning kerosene are about the same. What is intriguing from this example is that long-distance, flapping flight can be nearly as efficient as a modern transport aircraft even at the extremely low Reynolds numbers characteristic of bird flight! Could we build a 6 inch 747 and fly it 3,500 miles non-stop? Probably not, since the best endurance performance to date of a six-inch aircraft (Micro-Air Vehicles program sponsored by DARPA) is reported to be on the order of 20 minutes. The reason, of course, is that birds are far more sophisticated (and efficient) than our engineered solutions at that scale. We have yet to

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produce even a crude approximation of the biological sensory system that maintains aerodynamic control of a small vehicle in gusty wind conditions, that avoids headwinds or utilizes tailwinds, or that can produce reliable flight power for days without refueling.

The above example suggests two things. First it illustrates that while engineered systems are quite good at the scales required for human transport, natural flight systems are better at small scales. Clearly, large-scale transport aircraft can be improved, but at that size, fixed wings make a lot of sense and these airplanes are unlikely to sprout flapping wings. Second, at small scales, birds seem to have a distinctly better power supply and a significantly better control system. Micro-UAVs are, at present, suffering from inadequate range and poor stability in gusty conditions. Nonetheless, the recent interest in small-scale UAVs for data collection, data relay, surveillance, and even planetary exploration has heightened awareness of the need for such vehicles. The design of these vehicles may well benefit from a fresh look at biological flight systems. These small vehicles will operate at relatively low Reynolds numbers[13] and may have VTOL/STOL/stealth requirements that may suggest an integrated lift and propulsion system (i.e., bird-like[14]). For these requirements, mimicking natural flight systems should be the first approach. Certainly, for applications where agility is a crucial requirement or where runways are not available, flapping wing flight is superior to fixed wing and is more efficient than helicopters.

One of the more fascinating aspects of flapping wing flight is the opportunity it offers for enhanced control. In the spirit of Bushnell[15], flapping wings provide more "knobs" to turn to create a desired flow field and its resultant control forces. Birds have at their disposal a number of flight strategies[5]. Within certain limits they can alter their gait, flapping frequency, flapping amplitude and stroke plane angle, as well as their wing planform, camber, twist and angle-of-attack, and they can do most of this within a single wing beat. This extraordinary degree of control allows an extraordinary degree of maneuverability, stability and range of speeds. Dial[5] states that, in terms of body lengths per second, a swift travels over four times as fast as an SR-71, and a barn swallow has a roll rate

approximately 7 times greater than an A-4 Skyhawk. This should not be very surprising, however, since small bodies (with small inertia) require only small forces to affect large changes, which is why the common housefly can often elude the swatter.

There are, in addition, certain morphological characteristics of avian (and marine creatures) that appear to be present for drag and/or noise reduction. Some of these have been adapted in modern airplane design (slats, flaps, vortex generators), but most of these engineered solutions were developed without reference to natural systems. A re-examination of some of the unusual morphologies found in nature may provide additional inspiration for new methods of flow control. Some of these morphologies are well known (shark fins, tip feathers), but doubtless there are others that have yet to be identified.

The Problem of Energetics and Scale

The fact that there seems to be an upper bound on the size of flying creatures speaks mainly to the limitations on the energy densities allowed by muscle-powered biological systems and to the structures required for high aspect ratio wings. The power required for flight at very low forward speeds (hovering) is large, since the entire body weight must be supported by flapping. As forward speed increases the induced drag component decreases and the power required drops. At very high forward speeds the profile drag on the body and wings dominates, and the power required increases again, thus producing a U-shaped curve of power versus forward speed[16]. The intermediate speed where the power is a minimum is usually assumed to be the most favored flight speed for the animal. Pennycuick[11] estimates that the power required for sustained forward flight (at the minimum power speed) varies as $m^{7/6}$, and the power available from the muscles varies as $m^{2/3}$. The result of this, of course, is that at some point the power required exceeds the power available and sustained flight above that size is not possible. Figure 5, adapted from Pennycuick[11], illustrates this, and coupled with the empirical fact that the largest birds are on the order of 25-30 pounds, provides a scale for the crossover point. Following the analysis of Pennycuick, thousand pound birds do not

exist because muscle tissue alone cannot provide enough power (and because of the inertial and structural problems associated with large, flapping wings).
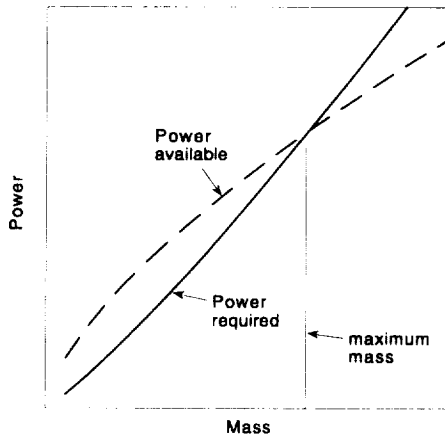

Fig. 5. Power available and power required for level, flapping flight (after Pennycuick, ref. 11).

In terms of mass specific power (power per unit mass) the previous relationships become:

$$(\text{power/mass})_{\text{required}} \sim m^{1/6} \qquad (2)$$

$$(\text{power/mass})_{\text{available}} \sim m^{-1/3} \qquad (3)$$

indicating that the required power per unit mass increases weakly with size, while the power available per unit mass decreases slightly with size. Ellington[17], however, argues convincingly that while the available data support the assertion that the mass specific power required does indeed vary somewhere between m^0 and $m^{1/6}$, the mass specific power available may actually increase slightly with size. He suggests that the power available varies roughly with $m^{0.13}$, but for some groups may be nearly independent of size. If we accept the larger exponent (0.13) the end result is that both the power required and the power available increase with size in approximately the same manner, which effectively removes the restriction that available power limits size in flying animals. Fossil remains of prehistoric flying reptiles indicate that at one time much larger creatures were capable of flight, giving some credence to Ellington's argument.

As a useful approximation, Ward-Smith[9] and Lighthill[18] estimate that the power available from muscle fiber is about 200 watts per kilogram (91 watts/lb$_m$), and with 20% of the body mass comprised

of muscle, the power available for flight is on the order of 40 watts per kilogram (18 watts/lb$_m$) of body mass.

It is not axiomatic, however, that biological scaling arguments strictly apply to engineered, flapping flight systems. Developments in energy storage technology may provide high energy density, lightweight, polymer batteries that actually form part of the structure. These new batteries, combined with advanced, composite materials may result in engineered flight systems that can exceed the performance of biological systems, not only in the power available per unit mass, but also in the power required per unit mass.

The aerodynamics of biological flight vary greatly with scale, but all biological flight is at relatively low Reynolds numbers (large marine animals being an exception to this) compared to most engineered systems. The wing chord Reynolds numbers can vary from roughly 10^1 for small flying insects to approximately 10^5 for large, fast-flying birds[19]. At the lower end of this range small insects are simply swimming in a viscous "sea" and aerodynamics plays a minor role. At Reynolds numbers this low conventional airfoils perform poorly, and nature has developed small-scale wings that are little more than corrugated, curved plates[6,8]. At the top end of the biological Reynolds number range large birds use conventional airfoil circulation to produce lift[9,19], although lift coefficients are lower and drag coefficients are higher than modern airfoils due to the relatively low Reynolds numbers[12]. Of course, bird and insect wings cannot be fully characterized as simple, 2-D fixed airfoils since the flapping motion introduces an aspect of unsteadiness to the flow. This unsteadiness, coupled with a dynamically changing angle-of-attack, planform, and wing twist during the stroke cycle, introduces a complex, 3-D flow field that, in some cases, cannot be accurately analyzed using normal steady state airfoil theory. The issues involved in unsteady aerodynamics, especially as they relate to flow control will be discussed in more detail in a later section.

In summary, biological flight may have certain scale limitations. Too large and the required wing area cannot be flapped with the necessary frequency; too small and the Reynolds numbers are so low that sufficient circulation-based lift cannot be generated,

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requiring unsteady mechanisms to provide the necessary lift.

Transition

Low Reynolds number airfoil flows are extremely sensitive to the location of transition. Conventional airfoil performance deteriorates rapidly for chord Reynolds numbers below about 10^6. Largely, this is due to laminar boundary layer separation at or near the beginning of the adverse pressure gradient on the airfoil upper surface. This separation produces a laminar free shear layer, which transitions to turbulence and reattaches if the Reynolds number is high enough. For low chord Reynolds numbers no reattachment occurs at all and the entire upper surface is massively separated. As one might expect, large increases in drag and loss of lift are experienced when large regions of separated flow are present. Unfortunately, the relevant chord Reynolds numbers for most birds fall in this range, $10^4 < Re_c < 10^5$, where airfoils can give unexpected results depending on where transition occurs[20,21] (see figure 6). This is compounded by the fact that birds may fly in high free-stream turbulence (gusty conditions), and, as just discussed, they produce dynamic changes in their wing shape and angle-of-attack through the wing beat cycle. Also, the relatively rough surface of bird wings may promote transition. As a result, the performance of bird and bat wings is likely to be extraordinarily sensitive to the location of transition and/or separation[12,22].
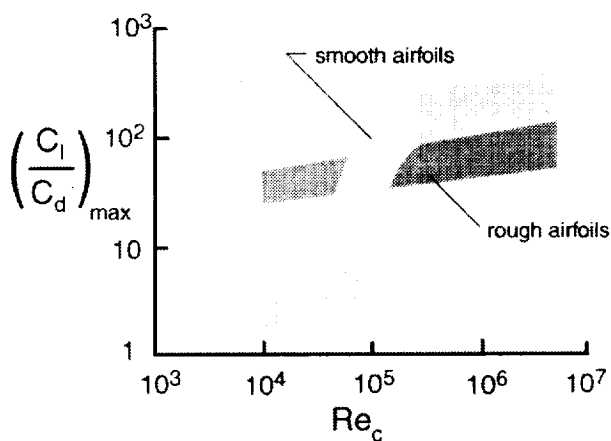

Fig. 6. Low Reynolds number airfoil performance (after Lissaman, ref. 20)

Little information on transition on bird wings is available. The work of Withers[12] shows a significant separated region for a nighthawk wing even at an angle-of-attack of $-2°$. At $+7°$., the wing is massively separated, but these measurements were made on a stationary, not flapping, wing. No transition measurements were reported in this experiment. Clearly, in order to build an accurate computational model of flapping wing flight at low Reynolds numbers, information on the state of the boundary layer will be required.

Insects fly at even lower Reynolds numbers, $10^1 < Re_c < 10^4$, and most of their wings are simply flat or curved, corrugated plates[6,8]. At Reynolds numbers this low the boundary layer is probably completely laminar and the corrugations (likely present to strengthen the wing structure[8,22]) may have little aerodynamic importance except to provide folds for trapped vortices that effectively camber the wing. Spedding[22] and Newman, et al.[23] show that for Reynolds numbers on the order of 10^4 dragonfly wings or simple curved plates perform better than airfoils.

In summary, transition on bird and insect wings at low Reynolds numbers remains a largely unexplored area and significant work needs to be done to guide modelers and designers of flapping wing vehicles.

Flapping Flight Kinematics

The flapping flight of birds and insects involves a complex range of wing motions that has yet to be fully characterized, especially with regard to unsteady effects, which assume more importance as scale decreases. Hertel[24] shows a close correlation between weight and stroke frequency for avian vertebrates, with hummingbirds having the highest frequencies (~70 to 100 hertz) and large birds the lowest (the wandering albatross, with its 11.5 foot wingspan, is hardly able to flap its wings at all!). Pennycuick[11] indicates that most birds are able to vary the wing beat frequency somewhat, but the maximum frequency varies inversely with the wingspan while the minimum frequency varies inversely with the square root of the wingspan. This means that as size increases the range of stroke frequencies available decreases

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until, at some point flapping at any frequency is impossible. The upshot of this is that the performance of large soaring birds can generally be estimated using conventional, steady (or quasi-steady) state aerodynamics since their stroke frequencies are rather low, but small birds and insects are a different story. Studies by Dudley et al.[25], the seminal work by Ellington[26,27,28] and the investigations of Dickinson et al.[29] have shown that insects use unsteady effects to great advantage, and, in fact, "cannot fly according to the conventional laws of aerodynamics". Dudley[6] reports that wing beat frequencies for insects range over three orders of magnitude and are inversely proportional to body size. The lowest recorded wing beat frequency for an insect is 5.5 hertz (damselfly), and the highest is 1046 hertz for a ceratopogonid fly. In contrast to vertebrate flyers, individual insect wing beat frequencies are fairly constant. Dudley states that the likely explanation for this that insects appear to use a resonant mode of flapping and any deviation from this preferred frequency incurs a substantial energy penalty. More discussion of insect kinematics and aerodynamics will follow in the section on unsteady aerodynamics.

For flapping flight it is necessary to define, in addition to the Reynolds number, another parameter that characterizes the wing beat frequency. Spedding[22] defines three, related reduced frequency parameters:

$$k = \omega c / 2U \tag{5}$$
$$\Omega = \omega b / U \tag{6}$$
$$K = 2\Phi n r / U \tag{7}$$

The parameters k and Ω are related by the aspect ratio AR, and the parameter K is the inverse of the advance ratio, J, when $r = b$ (the wing length):

$$\Omega = kAR \tag{8}$$
$$J = 1/K = U/2\Phi n b = \pi/\Phi\Omega \tag{9}$$

The advance ratio (borrowed from propeller theory) is, in this case, a measure of the forward flight speed to the mean wing tip velocity. It varies between 0 (hovering flight, $U = 0$) and infinity (soaring flight, $n = 0$). According to Dudley[6], when $J > 10$ steady flow predominates, but for $J < 10$ unsteady effects can be

important. For insects, Dudley also points out that their standard cruising speed is almost always on the same order as the flapping velocity ($2\Phi n b$) so that J is always around unity (or less). Ellington[30] reports that some insects may be able to exceed $J = 1$ slightly, but warns that an advance ratio limit of approximately unity limits the maximum flight speed for a given flapping velocity, and that dreams of very high-speed, insect-based MAV will not be realized. Clearly, with $J < 1$ for most insects, unsteady effects must be considered. For birds, bats and some large insects with slow flapping speeds, k and Ω may be sufficiently small and J sufficiently large for quasi-steady methods to apply[30], but exactly where unsteady effects become important is still uncertain. Spedding[31] correctly points out that there is no clear dividing line between steady and unsteady flow, and the magnitude of the unsteady effects should be estimated for the particular problem considered. For the purposes of this paper, we will assume that larger-scale avian vertebrates in steady, forward flight can be analyzed in a quasi-steady manner. Numerous reviews of the mechanics of the flapping flight of birds are available[9,11,22,32,33], and only some of the most important aspects will be reviewed here. Unsteady effects will be considered in a later section.

Lift is primarily produced by the animals wings (body lift is generally small[34]), and when extended as rigid, fixed airfoils (gliding flight) most animal wings easily provide enough lift to support the animal's weight. However, to produce continuous flight, the wings must be flapped. Flapping is necessary in order to tilt the lift vector in the flight direction for at least part of the wing-beat cycle. The thrust component thus produced must counterbalance the aerodynamic drag (skin friction, profile, and induced drag) for continuous, steady level flight. A wing-beat cycle where the wing is held in the same configuration for both the downstroke and the upstroke can produce a net positive lift, but no net thrust will be produced. Wing beat asymmetry, where some lift is sacrificed by varying the wing planform or by altering the bound vorticity, is required in order to produce a net thrust[35]. It is this asymmetry that flying animals adjust (within anatomical limits) to provide the required lift and net thrust as needed. Apparently, avian vertebrates have

developed at least two principal wing-beat methods, which are called gaits.

Gaits

Gaits in birds, much like gaits in horses, are characterized by a fundamental change in the kinematics of locomotion that is linked to speed[33,34]. Generally, birds exhibit two types of gaits, the vortex ring gait and the continuous vortex gait. Reference 34 further divides the vortex ring gait into two additional subcategories, but for the purposes of this discussion we will ignore that distinction. The vortex ring gait, as its name implies, is characterized by ring vortices left behind as the bird moves through the air. Generally, this is the result of lift being produced by the wings only on the downstroke. Circulation builds up on the wing at the start of the downstroke and a starting vortex is shed from the trailing edge with the ends attached to the wing tips. The bound circulation about the wing decays to zero at the end of the downstroke, and a stopping vortex is shed that closes the loop with the starting vortex. During the following upstroke the wing is highly flexed and little or no lift is produced. This gait is characteristic of slow flight in all birds[33] and is thought to be used by many species with short rounded wings, regardless of speed. In the continuous vortex gait the wings remain somewhat extended during the upstroke (but with the wingtips swept back), and approximately constant lift is produced on both the downstroke and the upstroke. Birds with long, or high aspect ratio wings with pointed wingtips (pigeons, falcons, gulls, petrels, and albatrosses), use this gait at high speeds. Since the wings are continuously producing lift, a stopping vortex is not shed and the trailing tip vortices are similar to the tip vortices of fixed wing aircraft. Rayner[33] discusses why the continuous vortex gait is limited to high speeds. Although the continuous vortex gait produces a positive lift component during the downstroke and the upstroke, the lift vector is tilted back during the upstroke, which produces a negative thrust. This negative thrust is small at high speeds, but becomes increasingly larger as flight speed decreases. If the bound circulation is varied on the upstroke (say, an angle of attack change) a small positive thrust can be generated on the upstroke at the expense of a small negative lift component. Birds have apparently solved the optimization problem by eliminating the upstroke lift entirely and shifting "gears" to the vortex ring gait at low flight speeds.

For small birds with low aspect ratio wings, which appear to use the vortex ring gait exclusively, Tobalske, et al.[34] speculates that these birds have only a fixed "gear", and in order to minimize power at high speeds they adapt an intermittent flapping motion. This intermittent motion is known as flap bounding. During a brief, powered phase the bird gains a small amount of height. This is followed by an un-powered phase where the wings are tightly folded and the body follows a more-or-less ballistic trajectory. After a small amount of height is lost the cycle begins again. Ward-Smith[9] presents a simple mathematical analysis of this flight style and shows that it can be a strategy to increase flight speed (over a restricted range) without increasing energy expenditure.

Tobalske, et al.[34], Rayner[33], and Ward-Smith[9] discuss many of the details of gait selection and flap bounding and the above description is meant only to emphasize that any efficient design of a flapping wing device must consider the aerodynamic consequences of the wing kinematics.

Stroke Plane

Another variable linked to speed is the stroke plane angle[35]. The stroke plane angle is defined here as the angle the wing-beat stroke makes with the horizontal. The stroke plane is nearly vertical (90°) for fast forward flight and is nearly horizontal (0°) for hovering flight. Clearly, from the previous discussion on gaits, avian vertebrates adjust the stroke plane angle to produce more or less thrust and/or lift to suit their needs. Small-scale birds such as hummingbirds utilize an almost horizontal stroke plane for long periods of time while feeding (100% lift, zero thrust), while a vertical stroke plane is used for high-speed flight where minimum lift and maximum thrust are required. Most birds appear to be able to hover briefly, or at least bring their forward speed nearly to zero for landing. The body is pitched up to a nearly vertical posture such that the wings are beating in a horizontal plane and forward speed rapidly drops. This capability is difficult to design into an engineered system, and no known ornithopters are able to take off or land on their own.

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Frequency and Amplitude

Vertebrate locomotion muscle requires a finite time to cycle, effectively setting an upper limit on contraction frequency, and hence, flapping frequency. According to Pennycuick[32] the time required for a muscle to be activated, shortened through its work stroke, and lengthened and reset for the next contraction is about 0.01 seconds; making 100 hertz a practical upper limit for flapping vertebrates (insects use fibrillar flight muscles which can cycle at higher frequencies). Birds are able to choose a flapping speed under this maximum, subject to some limitations. As mentioned earlier, reference 32 estimates that f_{max} is inversely proportional to wing length, or for geometrically similar birds, proportional to $m^{1/3}$. The minimum frequency, f_{min}, is inversely proportional to the square root of the wing length, or $m^{1/6}$. Figure 7, based on the analysis of reference 32, shows that above some maximum size, flapping flight is not possible within the constraints of the analysis. Of course, the actual upper limit on size may come from the limits on muscle power, as mentioned in the section on scale and energetics. From figure 7 it is clear that smaller birds have a wider range of frequencies available, but in practice it appears that birds prefer to minimize the power required. In order to do this the animal must adjust the wing beat kinematics with flight speed as was discussed in the sub-section on gaits. Rayner[33] has developed a theoretical model based on constant bound circulation, which would be appropriate for the continuous vortex gait. For this
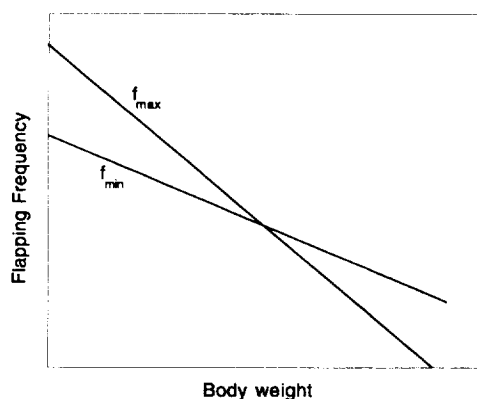

Fig. 7. Maximum and minimum flapping frequency as a function of size (after Pennycuick, ref. 32).

model, the lift is independent of frequency, but the thrust depends on both the flapping frequency and the amplitude as well as the spanwise distribution of circulation (details of Rayner's theory are available in reference 33). According to Rayner, birds select a combination of frequency and amplitude that minimize the power required at the chosen flight speed. Ward-Smith[9] suggests that the pectoral muscles of birds have an optimum contraction rate at which their efficiency is highest. Consequently, birds may not want to vary flapping frequency to any great extent from this optimum, and may instead vary only wing beat amplitude. Rayner (ref. 33) calculates the variation of frequency and amplitude with flight speed as predicted by his model for minimum mechanical power. Amplitude increases and frequency decreases as flight speed increases. Also, he shows a reduction in the reduced frequency and the trailing vortex strength with flight speed. The reduced frequency is simply the wingtip speed divided by the forward speed and therefore is a measure of unsteadiness. More will be said about this parameter in the section on unsteady aerodynamics, but for the present it simply indicates that at high forward speeds the reduced frequency is low and the quasi-steady approximation is valid.

Birds try to minimize power out of necessity since there are fairly hard limits on what muscles can provide. Engineered flapping flight systems will also have to minimize power usage for long endurance, but as better, lighter power supplies become available it may be that the biological limits are not applicable, and performance, at least for short periods of time, can greatly exceed biological systems.

Twist, Camber, Planform and Angle of Attack

Nature has provided a wide variety of wing shapes. However, both planform and angle-of-attack are known to vary during the wing beat cycle and it is likely that twist and camber also vary, depending on loading. Most bird wings have some built-in twist and camber. Ward-Smith[9] diagrams a cross-sectional view of a pigeon wing, indicating that relative to the root chord line the wing twists up to approximately +9 degrees at mid-span and back to + 5 degrees near the tip. The wing is also highly cambered near the root, but gradually flattens out as the tip is approached. Under

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loaded conditions this geometry undoubtedly changes since bird wings are truly aeroelastic structures. Modeling these aeroelastic effects for a flapping wing device will be challenging, and it is likely that new materials will be required to mimic the bone and feather structure of birds.

Lighthill[35] and Ward-Smith[9] provide a simplified analysis of the wing angle-of-attack motion by separating the processes of lift and thrust generation. In a coordinate system fixed with respect to the bird, the angle of attack of the wings is near zero during much of the downstroke, but is strongly positive during much of the upstroke. Wing planform is also significantly different between the two half-strokes, especially for the vortex ring gait where the wing is brought in close to the body on the upstroke to minimize drag. No lift is produced during the upstroke. For the continuous vortex gait, the bird can both produce thrust and keep lift approximately constant by sweeping the wingtips back and varying the angle-of-attack on the upstroke. These complex wing motions must be well understood before studies can be done to determine the best kinematics for an engineered system. Biologists have concentrated on understanding how biological creatures fly, but engineers must come up with an optimized design for a specific purpose. To do that requires that the flapping wing process be modeled in sufficient detail so that computational solutions can be used to find the best design for a specific purpose. Little appears to have been done computationally, and this is clearly a need, both for bird and insect flapping flight.

Flow Control Morphologies And Flight Strategies

Birds have a number of distinctive morphological features that may be used for flow control. In addition, they seem to have certain behavioral characteristics that suggest that they sense and use atmospheric dynamics to their advantage to conserve energy. A brief review of some of these features will be presented here, but the reader should refer to the cited references for more detail.

Tip Feathers, Alula, and Tails

The outer, separated primary feathers on some large soaring birds (fig. 8) have intrigued aerodynamicists for many years. The spread feathers were speculated to modify the shed vorticity from the wingtip and lower the induced drag. Cone[36,37] calculated the induced drag

Fig 8. Spread tip feathers on a Bald Eagle.

efficiency factor for several complex, non-planer wing designs and found that a branched tip design, much like the spread tip feathers of fig. 8, increased the effective aspect ratio over a flat wing by 20 to 30%. Cone speculates that this is an effective way for birds with a limited aspect ratio to obtain a higher effective aspect ratio. The upturned tip feathers effectively spread the trailing vorticity over a large vertical area, lower the effective downwash velocity and reduce the overall induced drag. Blick, et al.[38] conducted an experimental study using actual tip feathers from a wild Canadian goose attached to a rectangular NACA 2418 airfoil. The vorticity downstream of the wing appeared to be significantly reduced, at least along the line traversed by the measurement probe. Kokshaysky[39], Lighthill[18] and Oehme[40], on the other hand, suggest that the main function of the separated primaries is to allow an increase in the effective angle of incidence without stall, much like a multi-slotted wing and the tip feathers simply increase the total lift coefficient rather than reduce the drag. Perhaps the most comprehensive study of tip feathers was done by Tucker[41]. Tucker concluded from a theoretical analysis and from wind tunnel experiments with a solid wingtip, a natural-feathered wingtip and an artificial-feathered wingtip, that the slotted tips of bird wings reduce the induced drag. They do this in the sense that they increase the

effective span of the wing, as proposed by the original theory of Cone[36]. Slotted tips do increase the profile drag of the wing, however at the low speed of most of these birds induced drag is more important. Tucker also points out that certain sea birds (gulls and albatrosses) usually have longer, narrower, pointed tip wings that do not utilize slotted tips (fig. 9). This is presumably because they already have sufficient aspect ratio, and at

Fig. 9. Pointed wing tips on a Wandering Albatross.

the generally higher wing loading of these birds they must fly at higher speeds, which makes slotted tips costly in terms of profile drag.

It seems that this is an area that could benefit from some careful, non-intrusive flow field measurements such as LDV or PIV to quantify the vorticity distribution in the tip vortex system of a branched wing tip. In particular, it would be useful to compare Cone's inviscid, incompressible theory[36] with measurements and with Navier-Stokes calculations. Optimization studies could be done with a reliable code to see if further improvements could be made, or to find the best compromise between reduced drag-due-to-lift and increased profile drag. Cone also examined simple end plates and fins on wingtips and again showed significant gains over flat wings. The winglet, used on subsonic transport aircraft, is just such a tip modification, but the origin of the winglet idea was probably not linked to either Cone's work, or to biological flight systems.

The alula or hand wing is a separate collection on feathers on the wing upper surface that is controlled by the thumb[42]. The biomimetic review paper by Bechert[43] gives a beautiful picture of the alula in action. The hand wing appears to be drawn up automatically by large suction pressures developing on the upper surface

of the wing at high angles of attack and low forward speeds[9]. Here the physics appears to be similar to the slat on a high-lift system where the slat moderates the suction peak on the main airfoil, keeping the boundary layer attached.

Most birds have no difficulty flying without their tails[11,18,32]. Longitudinal trim changes in fast glides are largely achieved by fore and aft movements of their wings[32]. Roll is also controlled by rotating each wing to a different angle-of-attack and/or by retracting one wing at the wrist or elbow[11,18]. Pennycuick[11] notes that early forms of birds and pterosaurs had long tails, presumably for stability and control. Later groups dispensed with the tails, and Pennycuick speculates that this is because tailless flight is more efficient. The tail is, of course, used for supplemental control, especially at low speeds for landing and take-off where it also forms an additional lifting surface. Since we now have the ability to build and fly unstable designs, tailless aircraft are again of some interest, but biological systems seem to have solved this problem long ago.

Drag/Noise Reduction and Separation Control

Bechert's 1997 review[43] of separation control and drag reduction methods used by biological creatures lists surface treatments such as shark skins, hairy surfaces and self-cleaning lotus leaves, and separation control techniques such as vortex generators and movable flaps. The latter two of these techniques, vortex generators and movable flaps, are used by birds. Figure 10 from ref 44 shows the hooked barbules on the leading edge of an owl wing.

Fig. 10. Hooked comb on an owl wing, magnified 20x (from ref. 44).

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Owls approach their prey in gliding flight[45] to avoid flapping noise, but excessive noise from a massively separated wing also must be suppressed[46]. Owls also have a fringed trailing edge (fig. 11) that is also thought to suppress noise[46].
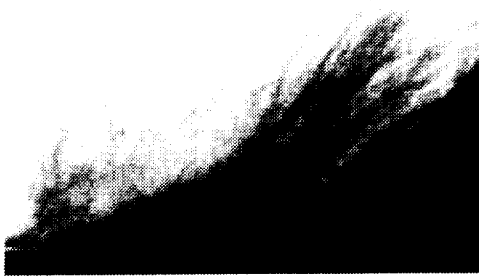

Fig. 11. Fringed trailing edge on an owl wing,, magnified 30x (from ref. 44).

The barbules (or combs) probably function as vortex generators[43] that bring higher momentum fluid down into the boundary layer and delay separation at high angles-of-attack. Vortex generators have been used on aircraft for years so no new technology is proposed by the natural example just given. The point to remember is that this is a low Reynolds number biologic flow control technique that works equally well on an engineered flight system at much higher Reynolds numbers.

Bechert, et al.[43] also discusses the use of "fluttering" feathers on birds for separation control. It has long been noted that birds have "popup" feathers that are deployed in high angle-of-attack situations, and these feathers seem to flutter when in the raised position. It is not clear whether these feathers are individually controlled or whether their action is automatic, much like the assumed action of the alula (hand wing) mentioned earlier. Bechert conducted a series of experiments with small, hinged flaps on the upper surface near the trailing edge of a laminar wing section. The flaps were free to lift according to the flow direction over the rear of the airfoil. When separation moved upstream from the trailing edge to the flap location, the flap lifted. This action delayed further upstream progress of the separation point and increased the maximum lift by about 10%. Flight experiments on

a sailplane were conducted with similar positive results. Bechert, et al.[43] found that while a rigid flap works well at increasing maximum lift, a strong hysteresis effect was noted. Further experiments with small flexible flaps that flutter showed even better performance, increasing the maximum lift approximately 6% over the rigid flap case and eliminating the hysteresis. Bechert speculates that the fluttering flap is extracting energy from the mean potential flow and feeding it into the near-wall region via a non-linear pumping action, virtually operating like an intermittent wall jet. It is not certain that this is the mechanism used by fluttering bird feathers, but it does point out the value of unsteady flow control. Reference 43 also discusses marine drag reduction techniques and these will be discussed in a later subsection of this paper.

Bounding Flight, Dynamic Soaring, and Formation Flying

Flap bounding, dynamic soaring, and formation flying are techniques used by avian vertebrates to minimize their expenditure of energy. The technique of flap bounding flight has already been introduced in an earlier section. Dynamic soaring simply refers to the process where energy is extracted from the dynamics of the atmosphere. Pennycuick[32] lists six different ways in which birds utilize the atmosphere dynamics to remain aloft, but all are essentially based on the idea that the atmosphere is not a quiescent pool of air, but contains micro-flows that birds can use to gain potential or kinetic energy. Most sailplane pilots are familiar with all of the techniques mentioned in reference 32: slope soaring, thermal soaring, gust soaring, frontal soaring, wave soaring, and wind gradient soaring. These techniques do not seem particularly well suited to direct flight from point A to point B at a specific time, since one must seek out the particular microflow wherever and whenever it occurs. However, large soaring birds do seem to be able to use wind gradients (shear layers between windstreams of different velocities, or the earth's surface boundary layer) to traverse, much like a sailboat, any direction except directly upwind. There is little new in the aerodynamics of these techniques and the reader is referred to Ward-Smith[9], Lighthill[18], Vogel[19], Pennycuick[32], Rayner[33], Tobalaske, et al.[34], Lighthill[35],

and Hendriks[47] for further discussion of flap bounding, dynamic soaring and formation flying. Long endurance flying of micro/macro UAVs will likely have to rely on such techniques (plus the use of tailwinds and the avoidance of headwinds) in the same way as birds do, but this appears to be a problem of sensing the environment and using it for some advantage, and not a problem with aerodynamics.

Bats

Birds and bats share much in common with regard to scale and flight kinematics, but bats have some interesting and unique morphologies that deserve a brief review unto themselves. According to Ward-Smith[9] there are approximately 800 species of bats, making them the second largest order of mammals. In addition, reference 9 indicates that this order has existed virtually unchanged for some 60 million years, which suggests that the flying mechanisms of bats (arguably the most acrobatic of all vertebrate flyers) has been optimized for some time. The size range of bats roughly overlaps that of birds, but the wing morphology is very different. Bats use a membrane wing stretched over extended digits on the fore limb, and the wing trailing edge (at the root) is attached to the rear limb. Figure 12 shows a sketch (in the style of reference 9) of a bat wing with the individual five digits identified. The wing is essentially a curved plate of variable camber with supporting ribs. The ability to modify wing camber by depressing the fifth digit gives bats an extraordinary amount of control, especially at low speeds.
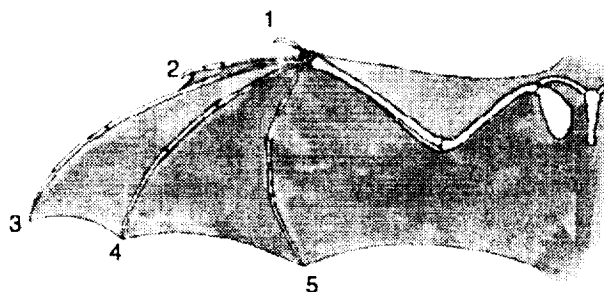

Fig. 12. Schematic of a bat wing.

A flap of skin attached to the thumb and extending to the shoulder is deployed in low speed flight[18] and functions much like a leading edge flap. The control, stability and maneuverability provided by a flexible, deformable thin airfoil has been noted by micro-air vehicle researchers[48,49]. A major problem facing the designers of these small vehicles is that of stability in gusty wind conditions. A membrane wing can be designed to twist under high load conditions, dumping lift and maintaining the vehicle attitude. Of course bats (and birds) do this by actively controlling their flapping wings, but current micro-UAV designs are simply fixed, membrane wings. One further note on rib-reinforced, membrane wings is worth mentioning. For larger scale UAVs (say 1-meter wingspan) the wing chord Reynolds number could be large enough to maintain a turbulent boundary layer over at least part of the wing, with an increased resistance to separation. The leading edge spar and other secondary spars could be shaped to provide a reliable source of disturbances leading to early transition on the wing upper surface. In fact, Ward-Smith[9] states that this likely occurs on bat wings where the humerus, radius, and the second and third digits of the hand serve as tripping devices, promoting turbulent flow. To this author's knowledge, there are no reported measurements on the state of the boundary layer on bat wings, but it would be very informative to conduct a transition study on a fixed, spar-reinforced membrane wing to see if the spars could serve as effective trips.

Unsteady Aerodynamics of Flapping Flight

For the case of very small insects, such as the fruit fly, *Drosophila Melanogaster*, unsteady fluid mechanics plays a crucial role. Dickinson, et al.[50,51] and Dickinson[52] studied the unsteady mechanisms used by the fruit fly using modeled flapping devices and live subjects, and it is worth detailing some of these results since these mechanisms may provide fresh inspiration for novel methods of flow control. Dickinson, et al.[51] has identified three unsteady mechanisms that may contribute to the aerodynamic performance of insects, which he terms delayed stall, rotational circulation, and wake capture. Insect wing strokes, according to Dickinson, can be divided into four separate motions (with some overlap). During the upstroke and downstroke phases, the wings translate at fixed

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(mainly) high angles of attack, although Ellington[27] argues that this is a very rough approximation for some species. Each half-stroke is then terminated by a rotational phase where the wings rotate and reverse direction. The overlap occurs because the rotational phase begins before the translational phase ends and continues into the translational phase of the next half-stroke. The wing rotation kinematics at the top of the upstroke were first identified by Torkel Weis-Fogh[53], which he termed the clap-and-fling (sometimes called clap-and-peel) mechanism.

Clap and Fling

In this mechanism the wings "clap" together at the end of the upstroke and "peel" apart at the beginning of the downstroke, rotating about their trailing edges and producing an initial strong bound vortex on each wing of equal and opposite sign. This fling-induced circulation can be large for high rotational velocities and enhance the downstroke lift. Spedding[21] cites earlier work by Spedding and Maxworthy[54], which found mean lift coefficients over the wing opening time as large as 6.9 to 8.5. Ellington[30], Dudley[6] and Maxworthy[55] provide good descriptions of the clap-and fling mechanism and the reader is referred to these papers for more details on this mechanism. Clap-and-fling is not used by all insects[30], however, and therefore cannot be the only source of unsteady lift augmentation.

Delayed Stall

Delayed stall is the generation of an attached vortex above an impulsively started wing, which increases the lift for two or more chord lengths of travel before detaching and being shed downstream. This large transient augmentation of lift occurs despite the well-known Wagner effect delaying the full development of circulation about the airfoil[56]. The Wagner effect simply refers to the fact that an impulsively started airfoil only develops 50% of its steady state circulation immediately, but must move through several chord lengths to reach the steady state value. If, however the wing is started at an angle of attack above its stalling angle, then a large transient vortex forms above the leading edge that dramatically increases the lift. Figure 13, taken from Dickinson, et

al.[29], shows the variation of the lift and drag coefficients with angle of attack for an impulsively started model airfoil (2D) at a low Reynolds number characteristic of a small insect (Re = 192).
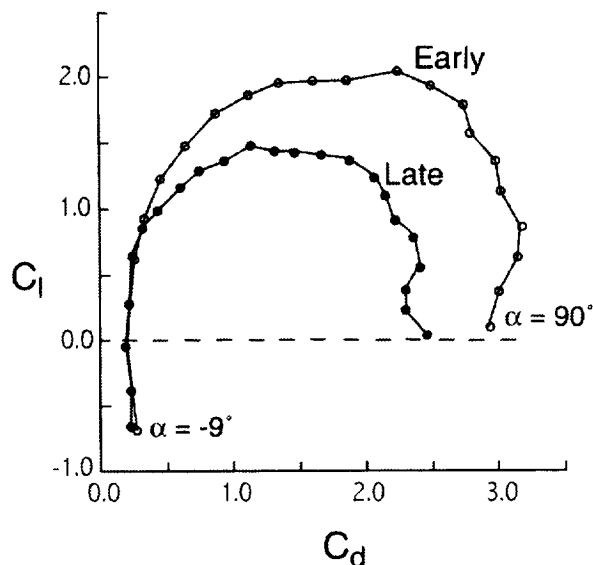

Fig. 13. Lift-Drag polar for accelerating airfoil (reproduced with permission from ref. 29)

The data are shown for 2 chord lengths downstream of the start (early) and 7 chord lengths (late). For angles of attack above approximately 13.5 degrees the lift is transiently increased (as much as 80% over that found at 7 chord lengths), and the drag is also increased. This increase in lift is significant since Dickinson states that a typical fly wing moves only 2 to 4 chords before reversing direction (half-stroke point). The flow over insect wings is inherently three dimensional, however, with a strong spanwise flow. Ellington[30] proposes that because of this spanwise flow the leading edge vortex assumes a spiral form that convects vorticity toward the wing tip where it merges with the tip vortex. This effectively limits the growth of the leading edge vortex, stabilizing it for the entire downstroke, thus making this mechanism effective even for relatively large insects such as the hawkmoth. The possibilities for using the delayed stall mechanism on engineered vehicles are intriguing, but the mechanism needs to be investigated in more detail (especially computationally) to determine its sensitivities to the wing morphology, wing kinematics and especially Reynolds number.

Rotational Circulation

The robotic wing measurements of Dickinson[52] showed two rotational force peaks at the end of each half-stroke, which he suggests originate from additional circulation produced by the wing rotation, much like the familiar Magnus effect. Because of the overlap between the rotation and translation phases the wing leading edge can rotate against the direction of travel (early rotation, producing backspin), or with the direction of travel (late rotation, producing topspin). By changing the phase of the wing rotation relative to wing translation Dickinson was able to produce positive or negative lift peaks (over and above that produced by delayed stall). Rotation of the wing before the beginning of the translational phase produced a positive lift peak; rotation after beginning translation produced a negative lift peak. In addition, Dickinson varied the rotational axis from the wing leading edge to the wing trailing edge and noted that the rotational lift decayed as the axis moved aft, in accordance with Ellington[28].

The opportunities for enhanced control using the rotational circulation mechanism appear to be excellent. All that is required to produce positive or negative lift is to vary the timing of the wing rotation relative to wing translation. Differential control of this timing (positive lift on one wing, negative lift on the other) could produce large moments and do it twice in every wing beat cycle. This, perhaps, partially explains how small insects achieve such remarkable agility and stability.

Wake Capture

The third unsteady mechanism suggested by Dickinson is that of wake capture. Essentially, in this mechanism the wing uses the shed vorticity of the previous stroke to produce additional lift on the subsequent stroke. Dickinson's experiments on the wake capture mechanism[52] are based on detailed studies of a flat plate airfoil in still air undergoing a translation phase followed by a rotation phase. In the Reynolds number range of this experiment (50 – 100) flow visualization studies show that periodic vortex shedding occurs for the flat plate airfoil at high angles of attack. Dickinson's measurements also show that when the beginning of the rotation phase precedes stroke reversal the airfoil intercepts its own wake so as to generate positive lift. Dickinson suggests that insects may use this effect to generate extra lift by adjusting their half-stroke length to match the distance between the shed vortices in the vortex street, and thus recover some of the energy lost to the wake on the previous stroke. The implication of this is that the stroke amplitude should scale inversely with the Strouhal number, but it is not clear that this scaling will hold at Reynolds numbers of practical interest.

Summary of Unsteady Mechanisms

The unsteady mechanisms just described are primarily found in very small-scale insects where chord Reynolds numbers seldom exceed a few hundred. It is certainly reasonable to ask whether these techniques can be used at Reynolds numbers more characteristic of engineered flight systems. Also, they clearly stem exclusively from the flapping action of the wings, and as such do not suggest immediate application to larger-scale, fixed wing flight. However, regions of unsteady flow exist on most fixed wing aircraft during certain parts of the flight envelope. A prime example is the landing approach of transport aircraft when the flaps and slats are deployed. The unsteady nature of the flow in the slat/main element gap of a typical high lift system was described in McGinley, et al.[57] and Paschal, et al.[58] as being large spanwise "rollers" emanating from the slat gap and convecting downstream over the upper surface of the main element. It does not require too much imagination to visualize an actuator in the slat gap, organizing and enhancing these vortices to provide additional main element lift using the wake capture mechanism described previously. However, exactly how these unsteady mechanisms will function at Reynolds numbers three or four orders of magnitude larger is still somewhat of an open question.

The recent research activities in small-scale uninhabited aerial vehicles (vehicles that may actually have flapping wings) could also benefit from an improved understanding of the unsteady fluid mechanics. It is a bit premature, however, to suggest that any of these techniques will find application until we have done some additional work to clarify the physics. What are most urgently needed are robust,

time-accurate computational tools to examine these unsteady flow fields. Little appears to have been done computationally, and with the large number of variables present in flapping wing flight, rapid progress in understanding will only come through computational experiments that narrow the playing field.

Marine Morphologies

The Reynolds numbers for aquatic creatures span approximately 13 orders of magnitude, ranging from 1×10^{-5} for a bacterium creeping along at 0.0004 in./sec to 3×10^8 for a large whale swimming at 33 ft/sec[16]. Ignoring for our purposes the lower end of this range, one might expect Reynolds numbers for marine animals of practical interest to be in the range $1 \times 10^5 <$ Re $< 3 \times 10^8$. Therefore, unlike the Reynolds number range for birds and bats, marine animal Reynolds numbers actually correspond closely to flight values for modern aircraft.

It is beyond the scope of this paper to attempt a full review of the rich field of marine animal morphology and marine propulsion techniques. The interested reader is referred to Lighthill[59,60], Wu, et al.[61], Childress[62], Cheer, et al.[63], Vogel[19] and various articles in section III of reference 64 for general descriptions of aquatic animal locomotion. More recently, Bandyopadhyay, et al.[65] examined some of the distinguishing morphologies of fish that are efficient in brisk maneuvers.

For the purposes of this paper I will briefly review some interesting marine morphologies that may be related to drag reduction. Most of these ideas are not new, and almost all were discussed in the 1991 review of Bushnell and Moore[66], but essentially no research has been done since that time to quantify or optimize any of their suggested mechanisms.

Perhaps the best example of marine morphology that has actually found its way into engineered systems is that of shark skin (see fig. 14). Berchert, et al.[43] examined shark skin in some detail and found that the skin friction drag on a shark skin surface can be reduced below that of a smooth flat plate by as much as 10%. Bechert's work followed work at NASA on riblets[67,68] which, although developed without
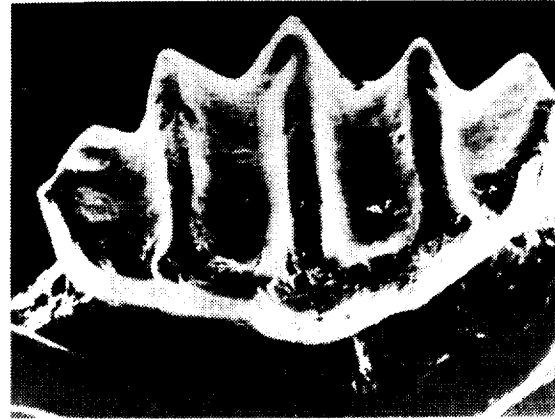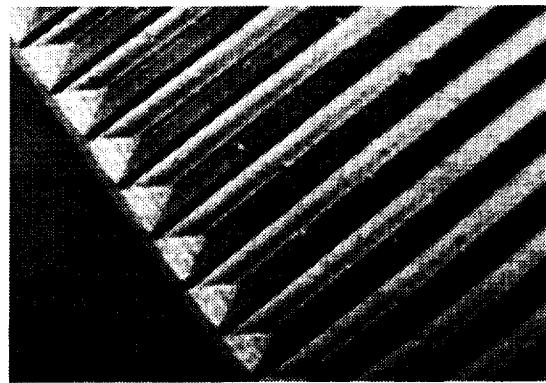

Fig. 14. Shark dermal denticle.

Fig. 15. Riblet film, 30x magnification.

biological guidance produced similar skin friction drag reductions with a similar V-groove geometry (fig. 15). Walsh[69] reviewed the development of riblets and the discoveries of shark skin morphology and gave an explanation of the physical mechanisms involved. Riblets and shark skin are mentioned here because they illustrate an example of the connection between biology and engineering. The correspondence between biological drag reduction and engineered drag reduction was unexpected, but it did provide an early encouragement to examine natural systems for other potential methods of flow control. Unfortunately, after a short, intense period of research in the eighties, this effort was abandoned by most, and only recently has there been interest in renewing research in the field.

Swept Tapered Tips

Any study of flight in both air and water immediately reveals that highly swept, tapered wing

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tips are almost universally required for high-speed motion of both birds and fish (see fig. 16). Lighthill[59]
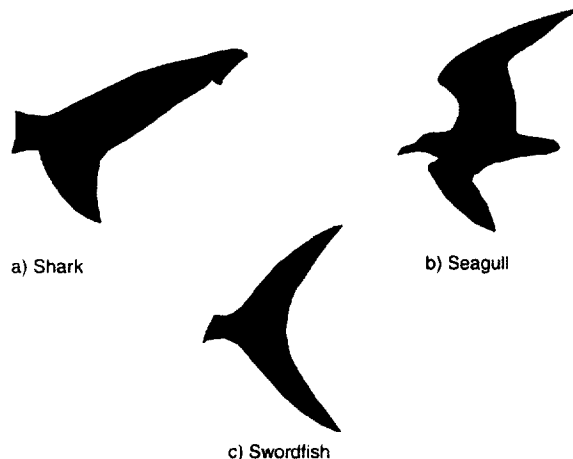

a) Shark
b) Seagull
c) Swordfish

Fig. 16. Swept, tapered tips in nature.

discusses the carangiform mode of fish propulsion and notes that most members of this group characteristically have a "scooped" caudal fin, forming a V-shaped profile with tips swept back 50 to 60 degrees. Within the carangiform group, survival-by-flight has evolved several families that have the highest speeds known in any kind of fish. Apparently, evolutionary pressures for higher and higher aspect ratio tails (to reduce the induced drag component) was moderated by structural limits and the V-shape tail evolved into what is commonly called the lunate, or crescent tail. Lighthill[59] argues that the lunate tail may be a favorable form because at the oscillation frequencies required for fast movement this shape sheds vortices of approximately circular form, perhaps minimizing the shed energy as a proportion of power exerted. Burkett[70] shows that swept, tapered tips can reduce the induced drag by 4% over an elliptic planform at moderate angles-of-attack (12°) as a result of the non-planer wake. Van Dam, et al.[71] conducted a 3-D, computational study of a swept-back tip and concluded that the outboard portion of a crescent-shaped lifting surface extracts more energy from the vortical wake than is predicted by classical wing theory, thus producing less drag for a given lift than for an elliptical circulation distribution. Reference 71 also examined a 3-D wing planform somewhat

similar to the subterminal lobe found on the heterocercal tail of some sharks (see fig 17).
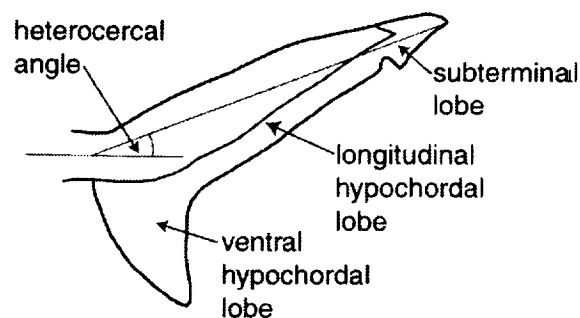

Fig. 17 Shark heterocercal tail.

The subterminal lobe morphology is thought to function much like a winglet that deflects under load to reduce the induced drag[71]. The results for the simulated shark tip also show an increase in the bound circulation distribution for the outboard portion of the wing over an elliptical distribution[71].

Swept, tapered tips are very common among biological creatures that depend on speed. The ability to flex under loaded conditions may be an important feature that has yet to be fully explored. Additional experimental and computational studies may be helpful in understanding how this feature could be applied to engineered systems.

Leading Edge Bumps

Another morphological feature that may have a drag reduction function is that of leading edge bumps. The nose of the hammerhead shark clearly shows a regular, spanwise array of bumps (see fig. 18).

Fig. 18. Hammerhead shark.

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This 3-D spanwise feature is also seen on the leading edge of some whale flukes, but is much less regular (see fig. 19). The action of the leading edge bumps may

Fig. 19. Humpback whale.

be to rotate the lift vector into the thrust direction[66], but computational studies need to be done to verify this. Trailing edge serrations have also been noted on humpback whale flukes and, again, this feature may be to reduce the lift-induced drag component.

Fins and Fillets

Fins and Fin-body intersections on sharks (fig 20) are sophisticated combinations of sweep, filleting and flexibility that may influence the strength of the necklace vortex. Almost a decade ago Bushnell, et al.[66]
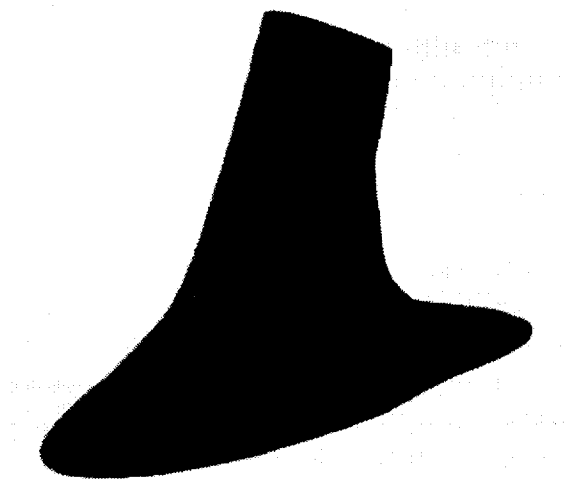

Fig. 20. Cast of shark dorsal fin showing filleted intersection.

pointed out that this may be a fruitful area of research, especially for maneuvering vehicles at an angle of yaw, but little has been done experimentally or computationally. Again, the fins are not rigid structures but deform under load, especially in the tip and trailing edge regions. This coupling of structural dynamics and aerodynamics is common in nature, but much less common in engineered systems.

Bluff Body Grooves

Body grooving is common in shellfish[19] and in cactus[66], and early work by Goodman and Howard[72] showed that large, longitudinal (flow-aligned) grooves
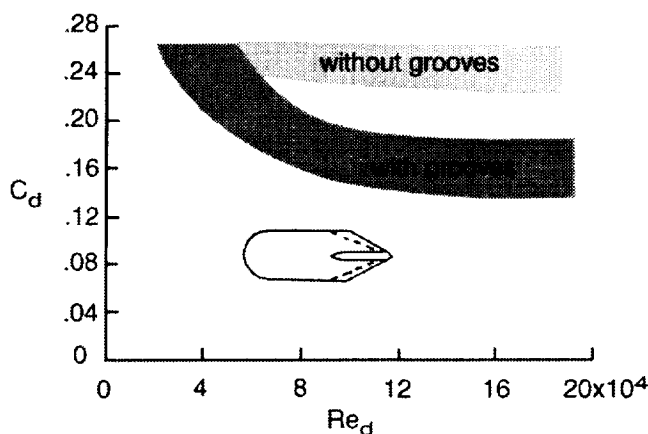

Fig. 21. Effect of longitudinal grooves on an axisymmetric bluff body (from ref. 72).

can reduce flow separation on the aft end of axisymmetric bluff bodies, yielding almost 40% reductions in drag (see fig. 21). In addition, circumferential grooves were also shown to reduce separation by substituting several smaller trapped vortices for a large separated region (see fig. 22).

Additional work needs to be done to determine optimal groove sizes, shapes and orientation, guided by the natural shapes seen in cacti and shellfish.

Miscellaneous

Bone[73] addresses a number of possible drag reduction methods used by fish. Among the techniques he lists are a) distributed dynamic damping (passive, porous bleed through subsurface canals), b) viscous damping (compliant surfaces), c) opercular slots (boundary layer blowing through gill slots at the beginning of the adverse pressure gradient), d) ctenoid scales (scales

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Fig. 22. Circumferential grooving to reduce separation (from ref. 72).

with comb-like downstream edges, i.e. micro vortex generators), e) caudal finlets and keels (vortex management), f) surface heating (warm muscle, reduced near-wall viscosity), and g) mucus (long chain polymer addition in the near-wall region). Most of these effects have been investigated to some degree[66] and it is well known that passive, porous bleed, boundary layer blowing, and micro vortex generators work as advertised. Some of the other techniques listed by Bone are a bit more problematic, such as surface heating. Although surface heating can reduce the viscosity of water it seems unlikely that the small temperature differences between a fish and the surrounding water could be significant[19]. Temperature differences large enough to matter would likely cost more energy than they would save in drag reduction. The same caution should be used with regard to mucus secretion. Vogel[19] states that continuous mucus secretion would be costly for the fish to maintain and it is likely that it is a beneficial drag reducing agent only in emergencies. Of course, whether fish use this mechanism or not does not

alter the fact that long-chain polymer injection into the near-wall boundary layer dramatically reduces the turbulent skin friction drag as evidenced by its daily use in crude oil pipelines.

Conclusions

What, then, is one to conclude from the preceding discussion? First of all, we must concede that avian vertebrates and insects have highly developed flight systems that are especially tailored for low Reynolds numbers, and that at very small scales they make extensive use of unsteady aerodynamics to offset the penalties associated with these low Reynolds number flows. Furthermore, the integration of the lift and propulsion system (flapping wings) allows them to create the unsteady effects that they use to stay aloft and control their flight. Additionally, biological power supplies and muscles appear to be superior to any engineered system we have been able to devise with respect to weight, reliability, and energy efficiency at that scale. Finally, birds and marine animals have a variety of distinctive morphologies that improve their efficiency in both air and water. Some of these techniques are already in use on modern aircraft, such as vortex generators and leading edge flaps and slats. Undoubtedly, there are other drag reduction morphologies that have yet to be fully characterized, including wing and fin tip shapes, fillet designs, grooves, 3-dimensional leading edge shapes, and others that have not yet been identified. Given these concessions, it appears that if we want to build small-scale, engineered flight systems, then it may be advantageous to study the mechanisms natural systems use to see if at least some of these techniques can be adapted to our uses. The wide variety of flight systems exhibited in nature present a significant research challenge to aerodynamicists, however. Trying to understand which systems are most efficient may be a fruitless task, since evolutionary processes are unlikely to move in a straight line toward "better" flight systems. Indeed, evolution may simply produce a random "spreading" of diversity[74], resulting in a pool of ever increasing (or sometimes decreasing) size.

Clearly, the recent interest in designing small-scale UAVs for remote data collection could benefit from a deeper understanding of avian flight mechanics.

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Although the military has a strong interest in mimicking birds and insects (flapping flight) for reasons of stealth, there are also many civilian applications of small-scale flying vehicles that could include both fixed wing and flapping wing devices. For example, one of the reasons our weather predictions are somewhat inaccurate, especially when predicting several days in advance is that we have insufficient initial conditions as input to our prediction codes. Currently, global weather information comes from satellite data, but detailed local information is limited to radiosonde balloons and land-based weather stations. Detailed data over the oceans is especially sparse, with few countries able to afford aircraft flights for data collection. It is easy to envision a "flock" of small-scale aircraft (probably fixed wing), dispatched to remote locations, loitering for days or even weeks on end, cooperating with each other to accomplish multiple tasks, and telemetering data back to receiving stations for a variety of purposes, including weather information, border and fishery surveillance, agricultural surveys, airborne pollution sensing, search and rescue operations, or even traffic control. Flying small-scale aircraft on long-endurance missions such as just described will require advanced, lightweight power supplies, advanced materials and structures, as well as sensor arrays that can find favorable atmospheric dynamics such as thermals and tailwinds and avoid unfavorable conditions such as strong headwinds. Birds do this on a daily basis, so it seems reasonable to suggest that understanding how natural systems work should be a first step in designing long-endurance macro-UAVs. Autonomous, meter-sized UAVs have already crossed the Atlantic (www.insitugroup.com), so the idea presented here is not unreasonable.

Admittedly, small-scale UAVs sharing the airspace with commercial and general aviation traffic (especially near populated areas) poses a major obstacle, requiring extremely high reliability and control, but this will likely be possible in future years with advanced air traffic control systems now under development that will allow precise ground control of both manned and unmanned aircraft.

The variety found in natural systems implies that there are many ways to design efficient flying or swimming devices and our current engineering thinking and practices should be broadened to include more novel ways of achieving our desired goals.

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