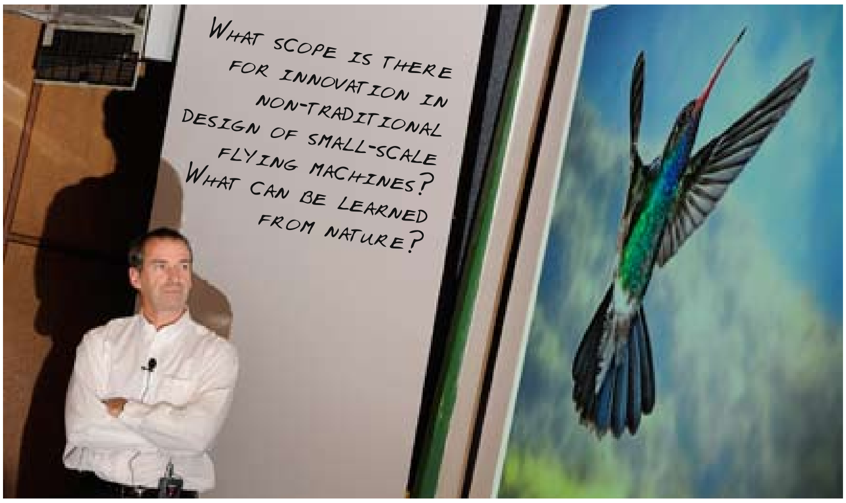
Flight at small scales

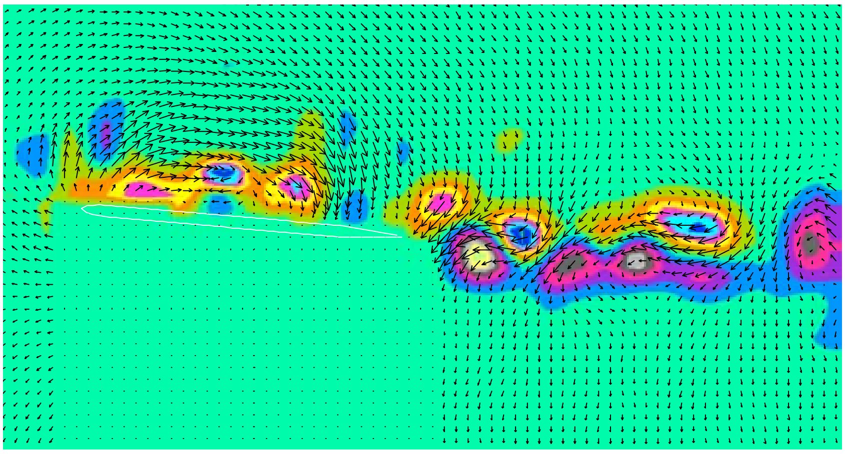
by Geoffrey Spedding



→ *Prof Spedding*

The promise of micro-air vehicles

A small aircraft about the size of your hand is hard to spot in the air, and can fly quietly on battery power, while manoeuvring through complex environments, like trees, buildings, hills and trenches. It can relay digital images back to its portable, laptop-based control station with refresh frequencies of 20 Hz, unobtrusively observing and monitoring. If it fails, its relatively low cost makes it practical and quick to replace; just throw another one up into the air. Thanks to the drop in size, and price, of electro-mechanical devices (driven recently by the cellphone industry), the reality of this vision is fast approaching.



→ *1. The flow over a flat plate at the maximum lift:drag ratio shows a boundary layer on the verge of instability. The angle of attack is 5°, and the flow, from left to right, is shown with the freestream removed. At $Re = 10^4$, the flow is complex. Nevertheless, the lift:drag performance is superior to most smooth aerofoil shapes, quite contrary to the findings at $Re > 10^5$, where we usually do our aerodynamics.*

Micro-air vehicles deployed by soldiers in the field can show who, or what lies over the hill, or round the corner. In search and rescue missions they can enter environments that are too dangerous or inaccessible, relaying chemical composition analysis as well as real-time imagery. With appropriate coordination, patrols can monitor fences and borders, and populations of top predators in large game parks. The business of coast-guards and lifeguards may change substantially.

So, where are they? Why have they not arrived yet? These are early days in the field. Military applications are driving much current research, and interesting problems in semi-autonomous control, communications and avionics must be solved. So too must some problems in aerodynamics. These problems are quite well-known to some but have not been considered important until recently.

Low Reynolds number flight performance

The Reynolds number, Re, is a product of the flight speed, U, times a flightwise wing chord length, c, divided by the kinematic viscosity, ν, and at sea level for a wing with $c = 6$ cm travelling at $U = 10$ m/s, $Re = Uc/\nu = 40\,000$. The same parameter for commercial aircraft typically lies in the range of $10^6 - 10^8$. When Re is on the order of 10^4 rather than 10^6, paradoxically, the prediction and measurement of flight performance becomes much more complicated. The aerodynamics are now very sensitive to the possible separation of the laminar boundary layer, and its further possible reattachment. Some famous results from the research literature show factors of two increase, or decrease, in drag over small increments in angle of attack (α). There can be hysteresis – where the lift:drag ratios for a given α are quite different depending on whether α is increasing or decreasing. Measurements from different facilities fail to agree on drag values, differing by factors of two, or more. The airflow is very sensitive to details of the aerofoil geometry, and to conditions in the wind tunnel test facility. Because of the requirement for resolving in detail the complex and time-varying motions in the thin boundary layer, there have been few, if any, computations that can predict the aerodynamics, and certainly none that can be used in any kind of turn-key fashion for design and performance testing.

There is a gap in the aerofoil performance data at moderate Re around 10^4, partly because of the lack of application and partly because of the extra degree of difficulty in achieving repeatable and generalisable results. Enormous care and attention to detail is required so that wind tunnel and model geometry properties are well understood. We have been performing the most simple possible experiments on the most simple possible shapes at these moderate Re, with the goal of linking the basic performance data with information about the physics of the flowfield. Figure 1 shows the instantaneous flowfield, coloured by the magnitude of the spanwise vorticity (a measure of the local shear and rotation), for a flat plate at $\alpha = 5^\circ$.

From simultaneous force measurements, we know that the lift:drag ratio in these conditions is a rather modest 7.8, but that this is still better than for a smooth Eppler 387 aerofoil section. The complex flow immediately above the upper surface of the flat plate shows why the maximum *L/D* has a sharp peak around a small range of α. The boundary layer flow itself is unsteady and the flow is constantly fluctuating there, close to forming a steady, persistent separation line. An extensive testing program is underway, measuring the properties of flat plates, cambered plates and selected smooth aerofoils, and tying the performance results in with flow data such as Figure 1. The wind tunnel turbulence levels are less than 0.025% for mean speeds of 10 m/s, and forces of 0.05 mN can be resolved.

In many respects it is remarkable that such tests are required at all. Surely, over the last 100 years, enough basic aerofoil shapes have been tested in enough wind tunnels by now? That is not the case at these Re, and computations have not been successfully made either, due to the same sensitivity to details of the laminar boundary layer behaviour and its possible transition to turbulence.

Can we learn from nature?

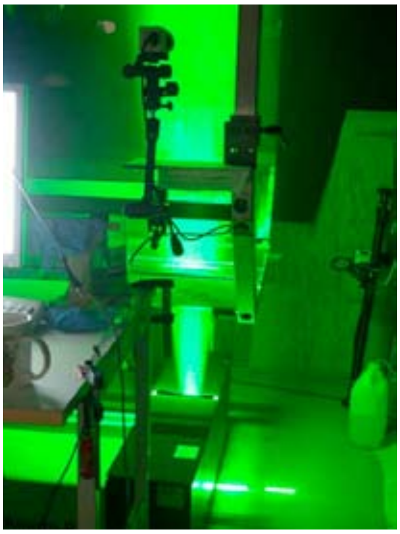
While embarking upon such a measurement program, one cannot help but notice that there are apparently successful proofs of concept already in the air, of around about the required size, in the form of birds. Not all birds look the same of course, and so questions about how they work quickly become more complicated questions about how a particular shape works and why. Consider the European swift, shown in Figure 2. The swift is a very interesting bird because it hunts and feeds in the air, attacking flying insects with tireless displays of aerobatics; it also migrates many thousands of kilometres from northern Europe to southern or central Africa, every year. It is an aircraft with both agility and endurance. In fact it is thought to land only to nest, and so in looking for an aerodynamic role model we may begin here.

The swift wing is peculiar in some respects too. It has a very distinctive curved leading edge, giving essentially variable sweep along the wing. The wing itself is also comparatively rigid, maintaining its shape throughout the wingbeat, and retracting rather little on the upstroke.

Inviscid, unsteady lifting-line theory shows that the curved centreline is an efficient shape for a pitching and heaving wing for aerial or aquatic propulsion, and this is likely why it is favoured by specially fast and/or efficient flyers like swifts, and also by swimmers like tuna, dolphins and fast sharks.

To see how the local wing section properties compare with those of other shapes, a wind tunnel test program has been conducted by a group headed by Prof A. Hedenström at Lund University, Sweden. An ingenious set of experiments conducted by Per Henningsson, introduced young swifts as they were about to emerge for their maiden flight, which then occurred in the wind tunnel itself. The birds were kept and flown every day for two

→ 2. The European swift, Apus apus. This agile predator can also migrate long distances and does everything except nesting on the wing. (Photograph by Jens Morin)



→ 3. Laser sheet created by a pulsed Nd:YAG emitting light at 532 nm, which is scattered off the fog particles in the wind tunnel test section. Each pulse contains 200 mJ of energy in about 5 ns, to give peak power densities around 40 MW. The laser sheet must be positioned safely downstream from the bird itself.
(Photograph by A. Hedenström)

→ 4. A bat in flapping flight towards the end of a turn in the Lund University wind tunnel. The wing membrane geometry is quite complex and varies considerably with time. The legs and long arm bones act to tension the elastic membrane stretched between them. (Photograph by A. Hedenström)

weeks and then released into the wild, seemingly unharmed by the experience. One cannot measure the forces directly upon a bird in flight, but the airflow around and behind the trained bird can be analysed to deduce the forces back on the wing. In an optical analogue of measuring drag from arrays of pitot tubes, the wind tunnel is seeded with a dilute fog, composed of smoke particles of diameter about 1 μm. When illuminated by sufficiently bright laser light, spread into a plane that is aligned with the flow, the individual particles can be imaged onto high-resolution digital cameras, and groups of these particles can be tracked statistically to estimate the instantaneous flowfield in a plane (this is also how Figure 1 was obtained, and Figure 3 shows an example of the laser light sheet in the wind tunnel test section).

The resulting reconstructions of the wake and calculations of forces from the momentum fluxes in both horizontal and vertical directions show that swift wings leave traces that differ quite noticeably from those of other birds in the same conditions. These differences can be traced back to the relatively rigid wings. In turn, these appear to give *L/D* ratios of up to 13, which are larger than any other bird yet measured, a fact that is quite consistent with our simplified theoretical models. If we were to build a flapping micro-air vehicle then it might be one that moves through the air, beating its wings in this way.

To flap, or not to flap?

There is one consistent feature that distinguishes birds from human-designed aircraft – birds flap their wings, planes don't. Simple scaling arguments can show why it is that commercial-sized aircraft are unlikely to be flapping their wings anytime soon, but now that we have moved our focus down to bird-size, maybe the issue should be revisited. Why do birds flap their wings anyway? Fundamentally, it is because they do not have a separate thrust generation mechanism, like a propeller or jet engine. In fact no animal has fully rotating machinery at the macroscale. The wings must provide both lift and thrust, without rotation (that rules out helicopter-like solutions) so they must flap. The most detailed current research suggests that flapping wings and propellers have rather similar aerodynamic efficiency, and so there is no compelling reason for either one to be any different. Birds can keep on flapping and micro-air vehicles can use whatever we are good at designing and building. However, there may be reasons to prefer wing flapping for control and manoeuvrability at bird-scales. We already have trouble with poor aerodynamic performance at the small scales of the wings. Even smaller flaps and auxiliary devices have even worse scale-related problems, and moving the entire wing may be an effective combined solution for both propulsion and control. Thus, engineering designs would retrace evolutionary paths where the two constraints have always been combined.

Bats

Bats use flapping flight too, and if the arguments for investigating flapping flight are persuasive, then perhaps the bat wing and its associated elastic membrane supported by long semi-rigid tubes will be one that is easier to engineer than a collection of feathers. Bats fly at night, so we notice them less, but they are very common and well-distributed around the globe. Many species have very impressive ultrasound sonar (termed echolocation) operating from 40 kHz – 200 kHz, coupled with agile, manoeuvrable flight for hunting down aerial prey. If we could build a bat, we might find many practical applications, perhaps even for nocturnal operations.

We have tested the flight characteristics of small, nectar-eating bats in wind tunnel experiments over their entire range of natural flight speeds, and have found measurable differences in the implied aerodynamic properties of the flapping wing membrane. The wing motions themselves are characterised by a very rapid backwards (relative to the body) flick of the outer part of the wing at the end of the upstroke.
Some birds do this too, and in the

absence of aerodynamic data it has never been clear whether this had some special significance, or whether it was more simply related to returning the wing as fast as possible to its beginning position.

In the bat experiments, we now see that the fast backward flick is associated with an extra lifting part of the upstroke, as can be deduced from the resulting air motions. In contrast to birds, it also appears that the two wings operate more independently, shedding vorticity at the wing root so that separate wake structures are associated with each wing. More puzzling, both outer and inner wings are associated with momentary negative lift at moderate speeds. It is hard to see a benefit to this, other than it being a necessary consequence of the requirement to keep the wing membrane under some minimum degree of tension before it collapses under load and creates a high drag. Thus the structure that appears to have some advantages in slow speed and possibly in manoeuvring flight, may exact a penalty in simple straightforward cruising flight. If we take our engineering design inspiration from these creatures, we may be faced with similar (and familiar) design trade-offs between cruise efficiency and agility.

Plans

The test and measurement program that began at the University of Southern California is moving to the University of Pretoria, where we will begin to measure accurate performance curves for fixed wings of various simple shapes, and at appropriate Re (this is what makes it new, and hard), while at Lund University experiments on different natural flapping wing geometries will also continue. As we learn more about the properties of different wing profiles at this difficult Reynolds number, where viscosity and inertia are in delicate balance, we hope to provide data and directions for both steady-state and unsteady designs.

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Recent articles in the technical literature:

Hedenström A & Spedding GR 2008 Beyond robins: aerodynamic analyses of animal flight. J. R. Soc. Interface 5, 595-601

Muijres FT, Johansson LC, Barfield R, Wolf M, Spedding GR & Hedenström A 2008 Leading-edge vortices increase lift in bat flight. Science 319, 1250-1253

Henningsson P, Spedding GR & Hedenström A 2008 Vortex wake and flight kinematics of a swift in cruising flight in a wind tunnel. J. Exp. Biol. 211, 717-730

Spedding GR, Hedenström A, McArthur J & Rosén M 2008 The implications of low-speed fixed-wing aerofoil measurements on the analysis and performance of flapping bird wings J. Exp. Biol. 211, 215-223

Hedenström A, Johansson LC, Wolf M, von Busse R, Winter Y & Spedding GR 2007 Bat flight generates complex aerodynamic tracks. Science 316, 894-897

Mini Unmanned Aerial Vehicle takes off!

The Department of Mechanical and Aeronautical Engineering at the University of Pretoria has developed a small unmanned aerial vehicle (UAV) for the purpose of game surveillance. The mini UAV is intended as a cost-effective alternative to current helicopter-based surveillance methods.

The UAV was designed for operation by a single person, requiring user control only during take-off and landing. Once at cruise altitude the UAV switches to autopilot control, under which it flies through a series of pre-programmed waypoints, beaming back surveillance pictures and video as required. Apart from the installed video camera, the aircraft is later to be equipped with a mini infra-red camera, adding the capability of night-time surveillance.

During the original design, the focus was to ensure that the aircraft is robust and easily repairable in the field, using standard parts and not requiring specialised knowledge or tools. The aircraft was developed and built by final year students in collaboration with specialists from the Massachusetts Institute of Technology (Col. Peter Young), Denel Dynamics (Mr Hennie la Grange) and the CSIR (Dr Bennie Broughton, Mr Peter Skinner, Mr John Monk).

Final year students Mark Müller and Wilmien Robberts this year developed a dynamic model of the aircraft and designed a control system for the autopilot. This was done under the technical supervision of Dr Bennie Broughton of the CSIR. The UAV has since successfully completed its maiden flight, with all systems functioning as predicted. Full integration of all flight systems is currently being conducted, and after extensive flight testing, the aircraft will be evaluated at the Pilanesberg Game Reserve.

Further information: Prof Leon Liebenberg, lieb@up.ac.za

→ Mini unmanned aerial vehicle of the Department of Mechanical and Aeronautical Engineering during its maiden flight in October 2008. The aircraft weighs 5.3 kg, has a wingspan of 2.5 m, and is designed to fly at altitudes of approximately 100 m above ground level at a cruising speed of 18 m/s, allowing it to fly for a maximum of 40 minutes.