Aerodynamics

Flight of the robofly

George V. Lauder

Qualitative studies of airflow over insect wings have long been possible, thanks to the use of smoke trails. With a new robotic fly, flow and force can be analysed quantitatively, so theories of insect flight can be tested.

The problem of studying how air moves around flying animals has attracted attention from zoologists, aeronautical engineers and computational fluid dynamicists, but has remained generally unresolved. It is terribly difficult to measure patterns of airflow accurately in three dimensions, especially around insect wings, which are typically small and move rapidly in a complex manner. Yet quantifying such patterns is essential for understanding the aerodynamic mechanisms of insect flight and for testing theories about wing function. On page 729 of this issue, Birch and Dickinson[1] describe how they used a dynamically scaled robotic insect to obtain new data on how insect wings function during hovering. The importance of their work goes beyond the specific hypothesis that they test, and shows the power of a laboratory model that combines quantitative analyses of airflow with direct measurements of the forces produced by wings.

J. M. BIRCH & M. H. DICKINSON

Figure 1 Robofly. Two model fruitfly wings, which can be controlled precisely in three dimensions, are attached to force sensors and immersed in a vat of mineral oil.

Our understanding of the aerodynamics of insect flight has been helped greatly by observations of tethered insects flying in a wind tunnel[2,3]. The introduction of smoke or dust streams into the tunnel allows researchers to observe how wing movements deflect oncoming air, and offered a first look at the vortices produced in the insects' wake. These data, combined with detailed analyses of wing kinematics in freely flying insects[4], provided a basis for evaluating theories about the aerodynamics of insect flight[5]. But it is extremely difficult to obtain repeatable data using live insects, and their small size complicates any effort to quantify airflow.

Against this background, five years ago Ellington et al.[6] published an influential paper showing that the insect wing supports a particular type of vortex, the leading-edge vortex. This is a region of rapidly circulating air, found near the front (leading) edge of the wing, with a low-pressure core. This vortex is stable during the wing's downstroke and might enhance lift, perhaps in part explaining how insects can generate surprisingly large lift forces. The authors were able to describe this phenomenon in detail because they used a mechanical model of a hawkmoth (the 'flapper') with a wingspan of over a metre, which allowed repeatable observations of airflow at a large scale. By injecting smoke directly along the wing's leading edge, the authors revealed that the leading-edge vortex had a helical structure.

Birch and Dickinson[1] have taken this approach considerably further. First, their dynamically scaled model fruitfly (robofly; Fig. 1) has two 19-centimetre-long clear plastic wings whose motion can be precisely controlled. The model is immersed in a large vat of mineral oil, making it much easier to quantify fluid flow over the wing using the technique of digital particle image velocimetry (DPIV) — an increasingly popular tool for studying the mechanics of animal locomotion in fluids[7–9]. By seeding the mineral oil with small air bubbles and illuminating a two-dimensional slice with a pulsed sheet of laser light, the movement of fluid above and below the wing and in its wake can be quantified with precision. DPIV obviates the need for creative interpretation of smoke trails. Furthermore, the light sheet can be repositioned along the length of the wing to construct a complete three-dimensional picture of flow.

Second, small force sensors at the base of one of the wings (where it joins the fly's body) make it possible to measure the forces perpendicular and parallel to the wing as it flaps, at the same time that DPIV data are acquired. Third, the wing can be manipulated (by adding fences across it to disrupt fluid flow from base to tip), as can the nearby environment (by building a wall curving around the wing tip).

Birch and Dickinson programmed robofly to move its wing in a hovering motion, and the result is the most detailed picture ever obtained of flow over an insect

wing. A beautiful tip vortex is visible, as is a strong downwash behind the wing, and lateral flow (from the base of the wing towards the tip) is seen along the rear two-thirds of the wing's upper surface (Fig. 2). The leading-edge vortex is also clearly present. However, it does not have the helical structure of the hawkmoth vortex, and fluid within the vortex does not flow significantly from the wing's base to its tip. This finding is noteworthy: leading-edge vortices on flapping wings are unstable and tend to break away, causing a rapid loss of lift. Visualization of smoke trails over the hawkmoth wing[6] suggested that leading-edge vortices are stabilized by strong lateral helical flow, but this is not apparent on the robofly wing.

So how might robofly stabilize these vortices? To investigate the problem, Birch and Dickinson eliminated all lateral flow by attaching teardrop-shaped fences perpendicular to the wing surface, with the fattest portion of the teardrop at the leading edge. Such fences should block any lateral flow and, if the present view of leading-edge vortices[6] is correct, should result in decreased lift. But the opposite occurred: the lift forces actually increased slightly when the fences were present. This makes it unlikely that insect equivalents of robofly — fruitflies — stabilize leading-edge vortices by lateral helical flow, and suggests that these vortices could actually grow larger before becoming unstable. Although there is considerable variability, the bodies of most insects are 2 to 4 millimetres long, equivalent to fruitflies. We must seek other mechanisms of vortex stabilization for such insects.

In the future, by changing the viscosity of the mineral-oil bath and the shape of the wings, it should be possible to use robofly to reveal the flow and force patterns around insects with longer wings, 2 to 5 centimetres long. Modification of robofly and the flapper to a state equivalent to forward flight would also be valuable. Ultimately, however, it may be possible to integrate DPIV with micro-electromechanical-systems technology, allowing simultaneous measurements of flow and force around freely flying insects. Then the insects themselves can tell us if our models are correct.

George V. Lauder is in the Department of Organismic and Evolutionary Biology, and the Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts 02138, USA.
e-mail: glauder@oeb.harvard.edu

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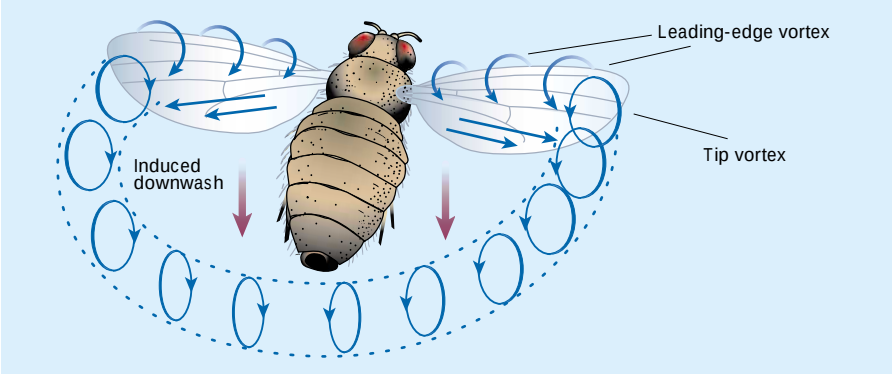

Figure 2 Patterns of airflow during the downstroke of a hovering insect, as revealed by Birch and Dickinson's quantitative analysis[1] of fluid flow over the wing of robofly. Airflow over the leading edge of the wing rolls up into a leading-edge vortex (LEV). LEVs contain a low-pressure core that enhances lift, but they are unstable and tend to detach, causing a rapid reduction in lift. This has prompted research into how insects stabilize LEVs during flight. One proposed mechanism is the lateral flow of air from the base to the tip of the wing[6]. However, when Birch and Dickinson installed barriers to lateral fluid movement on the robofly wing, an increase in lift occurred, suggesting that, for insects of fruitfly size, mechanisms other than lateral air movement must stabilize LEVs. The presence of a strong vortex at the wing tip and downwash behind the wing may stabilize LEVs by reducing the effective angle of wing attack (the angle between the wing and the oncoming air).