PAUL D. SAMUEL, DAEDALUS FLIGHT SYSTEMS, LLC & J. SEAN HUMBERT, UNIV. MARYLAND

An imitation insect, called a 'flapping wing micro air vehicle' does not resemble a bee, but it can hover in the air, turn rapidly and take off easily.

AERODYNAMICS

Vortices and robobees

A growing understanding of insect flight is helping scientists to build tiny flying robots.

BY NEIL SAVAGE

The flight of the bumblebee is a remarkable feat. These bees and related species can fly long distances to find flowers, then pause and hover in place, shrugging off powerful gusts of wind. They can zip around while laden with more than half their weight in pollen or nectar. And altitude is no issue.

Bees, together with hummingbirds and fruit flies, produce great lift, achieve high power output and exhibit exquisite control, says Robert Dudley, an integrative biologist and head of the Animal Flight Laboratory at the University of California, Berkeley. "These are amazing design solutions to specific problems that engineers are super-interested in." As some scientists work to tease out the details of bee aerodynamics, others are applying the lessons learned to aeroplanes and even to create tiny flying robot bees with a host of potential applications in disaster response, espionage and agriculture.

It is a popular misconception that science cannot explain how bees fly. This conundrum can be traced back at least to 1934, when two Frenchmen, zoologist Antoine Magnan and his colleague André Sainte-Lague, did some calculations and concluded that it was impossible for bees to fly, despite the clear evidence that they do. The problem lay not in the scientists' mathematics, but in their assumption that bees operate on the same principles as aeroplanes and gliders. "If you applied fixed-wing aerodynamic theory to the flight of a bee, you would have seen that the aerodynamics didn't work out," says Douglas Altshuler, a zoologist at the University of British Columbia in Vancouver, Canada. Aeroplanes rely on a steady flow of air, with the air above the wings moving faster than the air below, which generates lift.

DESCRIBING THE IMPOSSIBLE

Bees, of course, do not fly like aeroplanes — or even like most birds, which flap their wings up and down slowly. Bees beat their wings up to 240 times a second[1], which generates their noisy buzz and creates unsteady effects such as whirls and eddies in the air that surrounds them. If a plane created such a turbulent airflow, it would have problems, says Michael Dickinson, a zoologist and bioengineer at the California Institute of Technology in Pasadena. But in bees, such disturbances aid their ability to fly.

Some of these turbulent effects come from the angle of the wing, says Dickinson. Aeroplane wings are almost horizontal, generally deviating by less than 5°. At higher angles, wings create a leading-edge vortex — a tiny tornado turned on its side — that initially provides an enormous amount of lift. But at the trailing edge of the wing, the air stream above fails to reunite with the one below and the effect disappears, causing loss of lift known as a stall.

Bees' wings hit the air at ever-changing angles, often greater than 50°, which provides the insects with high-lifting forces, Dickinson explains. At the end of each stroke, the wing moves in the opposite direction, generating a new, opposing leading-edge vortex that gives it another burst of lift. And because it takes longer for the streams of air to separate than for the wing to finish each stroke, the bee's flight does not stall (see 'The secret to lift').

That mechanism is not the only source of lift, says Altshuler. At the end of the stroke, the bee actually flips its wing over, giving it a small amount of rotational lift too — a similar effect as putting backspin on a tennis ball. And because the wing has reversed direction, it is now travelling through disturbances from its previous stroke, so the air moves even more rapidly, enhancing the lift. "That is the wing recapturing its own wake," Altshuler says.

In addition to leading-edge vortices, rotational lift and wake recapture, bees can fine-tune their flight by varying the stroke length and, to a lesser extent, the speed[2]. "It's almost like there's a menu of different aerodynamic mechanisms," Altshuler says, "and depending on how they position the wing stroke, they can select from this menu."

HIGH FLIERS

Although the flight mechanics of bees are no longer mysterious, some of their aeronautical capabilities remain difficult to rationalize. Dudley travelled to Sichuan, China, to study honeybees[3] living in the Himalayas at elevations of 3,250 metres. He placed the bees in a portable pressure chamber and used an air pump to remove some of the air and simulate higher altitudes. The bees lengthened their wing strokes and all were able to hover at pressures equivalent to 7,400 metres above sea level. The champion bee reached 9,125 metres — well above the peak of Mount Everest, at 8,848 metres. Dudley found that the same bees could fly at the equivalent of 1,000 metres below sea level. He does not have a good explanation for this range of ability. "You just have to wonder, why would this come up in nature?"

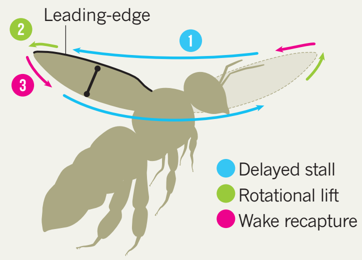
With such a suite of aerodynamic tricks, it is no wonder that engineers are using bees as inspiration in the design of aircraft. One thing that bees are very good at is coping with gusts of air carrying a force comparable to the speed and lift they are producing. The turbulence that a passenger jet experiences is many times smaller than its speed and lift, yet it causes a lot of discomfort to those on board; microbursts of air have caused planes to crash. A better understanding of how bees handle these forces might lead to new ways to cope with them in aeroplanes. "It's teaching us how to harness some of the unsteady effects and flow that we try to squash out," says Sean Humbert, head of the Autonomous Vehicle Laboratory at the University of Maryland in College Park.

A bee relies on tiny hairs covering its body to help it cope with different aerodynamic forces. Replacing existing aeroplane airflow sensors with ones that can detect localized forces, as a bee does, might give the plane's systems more-delicate control. If wind started to push the left wing upward, local sensors would detect those forces before they affected the rest of the plane, and the pilot could adjust the wing flaps so the plane would not rock. That sort of control will almost certainly be necessary, Humbert says, if a company ever wants to fly drones, or unmanned aerial vehicles, through the turbulent air of urban environments to deliver packages without crashing into roofs, playgrounds or other drones.

By carrying out experiments with bees in a wind tunnel, Humbert is learning how the insects' sensors alter how they fly. Based on these insights, he is working with the aerospace industry to alter the designs of drones. Improved drones for urban use could come within a year or two, he says. Systems to smooth out passenger plane flights, which would need new sensors and motors that can react quickly enough, may take longer.

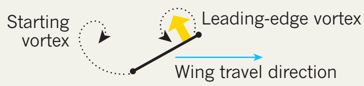
THE SECRET TO LIFT

Bees stay aloft through three main mechanisms. The process generates a burst of force during each phase.



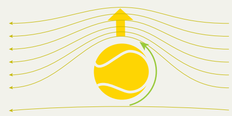
1. Delayed stall

During each stroke, the leading edge of the wing creates vortices that remain attached to the wing and stop the bee from stalling.



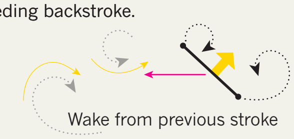
2. Rotational lift

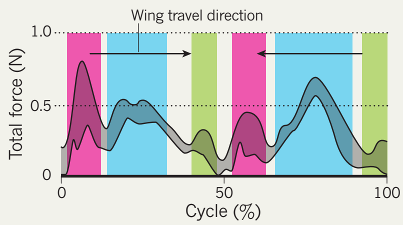
But the wing also rotates between strokes to create lift in a similar — but not identical — way as a backspinning tennis ball.



3. Wake recapture

Finally, the bee's wing is oriented on the upstroke such that it capitalizes on the wake of the preceding backstroke.





GRAPH SOURCE: REF. 1

Some scientists are trying to build machines that fly in the same way as bees. "We're trying to use the motions insects use, expecting to achieve similar forces and the ability to fly," says Jeffrey Pulskamp, a mechanical engineer at the Army Research Laboratory in Adelphi, Maryland. A fleet of tiny, expendable airborne robots would have both military and civilian applications. They could, for example, fly into buildings that have collapsed following an earthquake, hurricane or bomb blast. "Imagine being able to send a team of autonomous little vehicles in there to sense people or temperatures or chemicals," says Humbert, whose group is one of several working with Pulskamp's team. Robotic bees could fit into spaces that larger drones cannot go, slipping into crevices (and attracting less attention). Robotic bees could even be used as artificial pollinators, temporarily substituting for real bees — although because researchers are still in the early stages of creating these machines, that application could be 20 years away, says Robert Wood, head of the Robobees project at Harvard University in Cambridge, Massachusetts.

The first challenge was to get the tiny robots airborne. Pulskamp's team has built prototypes. The imitation insects have bee-sized wings — and motors to flap them — made of a thin film of the lightweight ceramic material lead zirconium titanate. The wings jut out from a thin sheet (the 'body') that is connected to a silicon chip by a tether that supplies power and keeps the platform stable. With this set-up, the researchers have achieved hovering flight.

> ***"It's teaching us how to harness some of the unsteady effects and flow that we try to squash out."***

Wood's Robobees project has also flown a tethered platform that has insect-scale wings made of a polymer membrane covered with spars of carbon fibre that resemble a bee's wings more closely. Wood made the wings by copying the insect originals and not worrying too much about how they worked; they were more for testing his motor.

Further into the future, micro air vehicles may need capabilities such as chemical sensors, infrared detectors and microscopic versions of Geiger counters to carry out tasks. Because the micro vehicles will be untethered, they will also probably require radio transmitters to communicate and global positioning system equipment. And to run the whole package, they will need computer control, all of which points to one of the trickiest aspects of making tiny autonomous flying robots: power. Five or six years ago, Wood says, a good polymer lithium battery that was small enough to fit on to a robobee provided enough power for 19 seconds of flight. Advances in the propulsion system, energy storage, motors and electronics means that Wood's estimate has increased to a few minutes. "But it still highlights the challenges with power for these small robots," he says.

All of these challenges — flight, navigation, control, power — will require several more years of work if scientists are to replicate the abilities that natural selection bestowed on bees. It took 50 years to explain how bees fly, and scientists still have not discovered all their secrets. ■

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1. Altshuler, D. L., Dickson, W. B., Vance, J. T., Roberts, S. P. & Dickinson, M. H. *Proc. Natl Acad. Sci. USA* **102,** 18213–18218 (2005).
2. Vance, J. T., Altshuler, D. L., Dickson, W. B., Dickinson, M. H. & Roberts, S. P. *Physiol. Biochem. Zool.* **87,** 870–881 (2014).
3. Dillon, M. E. & Dudley, R. *Biol. Lett.* http://dx.doi.org/10.1098/rsbl.2013.0922 (2014).