quick study

Dragonfly flight

Z. Jane Wang

Dragonflies have evolved for about 350 million years. What kinds of aerodynamic tricks have they discovered?

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Summer in Ithaca, New York, is a good time to watch dragonflies. At a glance, you can see that a dragonfly has a prominent head, an elongated body, and two pairs of slender wings extending to each side. As it takes off, the wings appear as a blur. In air, the dragonfly dances in unpredictable steps, hovering briefly then quickly moving to a new location. Just when you think it might stay long enough in the viewfinder of your camera, poof! It is gone. In contrast, an airplane, noisy and powerful, has a more straightforward way of going about its business. Propelled by engines and lifted by wings, it wastes no time in going from one place to another.

Lift and drag

Just as people do when they swim or row, planes and insects generate thrust by pushing a fluid. Unless the fluid flow is symmetrical, which is rare in nature, a wing experiences a lift force in a direction transverse to its motion in addition to a drag force that opposes its motion. As illustrated in figure 1, the lift can support the weight of a plane or provide a forward thrust to an insect or bird that flaps its wings in flight.

Animal and airplane flight can be characterized, in part, by the Reynolds number *Re*, a measure of the relative importance of inertial and viscous forces. For dragonflies, *Re* is 3000–6000; for an airplane it can be greater than 10 million. If *Re* is greater than roughly 100, both lift and drag are proportional to the product of velocity squared, fluid density, and wing area. That product can be interpreted as the rate of momentum transfer from air particles that hit the wing and bounce off. But if the particle picture were the whole story, planes would not be able to carry much nor would they be very efficient. Based on the particle picture, one would predict—as Isaac Newton did—a lift proportional to $\sin^2\alpha$ for a wing with angle of attack α. That's much smaller than observed, at least for a small angle of attack. The same calculation also predicts a maximum lift-to-drag ratio of 1 at an attack angle of 45°. The Wright brothers, in their artistry, achieved a lift-to-drag ratio of about 10 for their first flight.

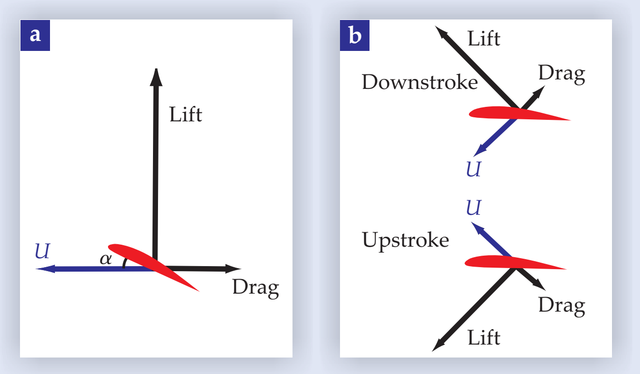

Figure 1. Aerodynamic lift and drag. Lift is the force component orthogonal to the wing velocity *U*, and drag is the component opposite to the velocity. **(a)** For an airplane with a small angle of attack α, the lift is upward and the drag is rearward. **(b)** A wing flapping up and down can fly into a headwind. In both the upward and downward strokes, the lift has a forward component that provides thrust.

Planes

What is not captured in Newton's calculation is the dramatic change in the flow that occurs near the edges of the wing, leading to "roll-up" of fluid and subsequent vortex shedding. The flow was mathematically modeled more than a century ago in the 1903 Kutta–Joukowski theory. One of the theory's predictions is that the lift is proportional to $2\pi \cdot \sin\alpha$, a result much closer to experimental values than $\sin^2\alpha$. In 1904 Ludwig Prandtl's boundary-layer theory allowed for a calculation of the drag on an airfoil (see the article by John D. Anderson Jr, PHYSICS TODAY, December 2005, page 42).

Nowadays, the lift-to-drag ratio can be on the order of 100 for a wing that tilts up just slightly against the flow and slices through the air at a small angle of attack. If α exceeds about 15°, however, the flow separates from the wing, the lift decreases, the drag increases, and the airplane stalls. Insects employ wing motions that are neither steady nor limited to a small angle of attack. What kind of tricks do they use to fly? Below I describe several lessons learned from dragonfly flight.

Dragonflies

Dragonflies flap and pitch their wings at a rate of about 40 Hz, creating whirlwinds as illustrated in figure 2. A peculiarity of the dragonfly is its use of a rowing motion along an inclined stroke plane. During hovering, the body lies almost horizontal. The wings push backward and downward, and at the end of the stroke, feather and slice upward and forward. In contrast, many other hovering insects use a symmetrical back-and-forth stroke near a horizontal stroke plane. The dragonfly's asymmetric rowing motion allows it to support much of its weight by the upward drag created during the downstroke; for the more common symmetric motion, the drag roughly cancels.

The dragonfly belongs to Odonata, one of the most ancient of insect orders. Its fore and hind wings are controlled by

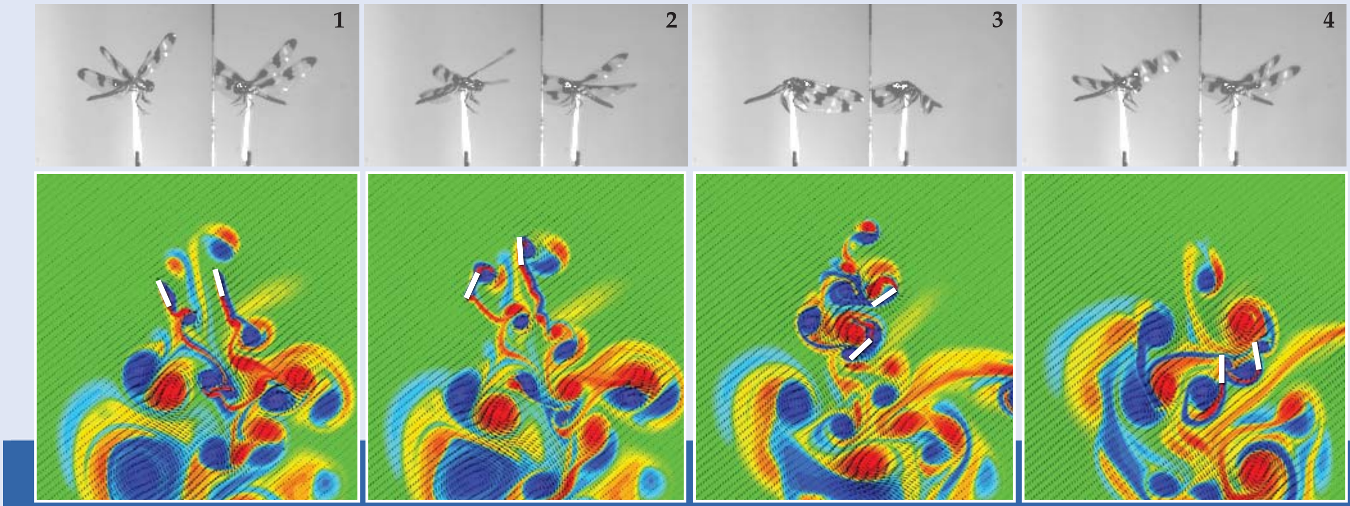

Figure 2. Stop-action dragonfly flight. The photographs on top show pairs of mirror-view images of a tethered dragonfly (*Libellula pulchella*) during one period of hovering motion. The colorful bottom images display calculated air flows at four representative times in the dragonfly's wing-stroke cycle. In these simulations the dragonfly's body is horizontal and its head is to the right. White lines indicate cross sections of the fore and hind wings, which are separated by about 1 cm. Red areas indicate counterclockwise swirling, blue represents clockwise motion.

separate muscles, and a distinctive feature of the dragonfly's wing movement is the phase relation between those wings during various maneuvers. When hovering, the fore and hind wings tend to beat out of phase; during takeoff, they tend to beat closer in phase. Why does a dragonfly vary the phase in different maneuvers? One plausible explanation is that alternating the downstroke reduces body oscillation. That is, however, only part of the story. The fore and hind wings are about a wing-width apart—close enough for them to interact hydrodynamically. To determine the amount of interaction, one solves the Navier–Stokes flow equations with boundary conditions set by the movement of the wings. The resulting flows are spectacular and complex. They depend on Reynolds number, wing motion, wing shape, and phase difference.

Despite that complexity, two general results emerge: The aerodynamic power expended is reduced when the wings move out of phase, and the force is enhanced when the wings move in phase. When the fore and hind wings beat out of phase, they approach each other from opposite sides and cross near the midstroke. The fore wings experience an induced flow due to the hind wings, and vice versa. As a consequence, the drag on the wings is reduced, as is the power expended in flapping. But the reduction in drag on the two types of wing points in opposite directions, so the net force is essentially unaffected. In other words, the counterstroking allows the dragonfly to generate nearly the same force while saving aerodynamic power. If, instead, the fore and hind wings beat in phase, they will experience a higher drag due to the induced flow. In this case the increase in drag on all the wings points in the same direction. Thus the hydrodynamic interaction results in a greater net force that can be used to accelerate as needed during takeoff. The cost is greater power expenditure.

Dragonfly wings are not entirely rigid. A close inspection of high-speed films such as the one used for figure 2 reveals a torsional wave that propagates from the wing tip to the root during pitch reversal. If the muscles were actively pitching the wing, one would expect the wave to propagate in the opposite direction, starting from the root where the muscles act. The observed tip-to-root direction suggests that aerodynamic force and wing inertia are responsible for pitching the wing. Indeed, one can compute the aerodynamic torque and inertial force associated with the observed wing motions and confirm that they are sufficient to pitch the wing for dragonfly and other observed hovering wing motions. An insect can take advantage of the natural swinging motion near the end of its wing stroke to simplify control and save energy.

Optimization

Why do insects move their wings as they do? Have insects found efficient motions consistent with their muscle and wing design? Such questions come under the rubric of optimization in biological systems. The associated issues are open to debate, but without testable predictions, it is difficult to make progress.

For insect hovering, one natural measure of optimization is energy minimization: An insect's metabolic rate increases by a factor of 50–200 when flying, and food does not come easily. A large part of the energy needed to fly is associated with the mechanical work needed to overcome fluid drag and wing inertia. To explore whether hovering insects using a specific wing minimize the mechanical energy expended to support a given weight, one can calculate the mechanical cost in an aerodynamic model and search for energy-minimizing motions. For fruit flies, hawk moths, and bumblebees, the predicted motions resemble the observed ones. It's a start.

Additional resources

▶ The webpage for Z. J. Wang's research group is http://dragonfly.tam.cornell.edu.

▶ S. Childress, *Mechanics of Swimming and Flying*, Cambridge U. Press, New York (1981).

▶ M. H. Dickinson, F.-O. Lehmann, S. P. Sane, "Wing Rotation and the Aerodynamic Basis of Insect Flight," *Science* **284**, 1954 (1999).

▶ Z. J. Wang, "Dissecting Insect Flight," in *Annual Review of Fluid Mechanics*, vol. 37, J. L. Lumley, S. H. Davis, P. Moin, eds., Annual Reviews, Palo Alto, CA (2005), p. 183. ■

The online version of this Quick Study includes further readings and a link to a video of dragonfly flight.