Dragonfly flight

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

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 $\sin \alpha$ for a wing with angle of attack $\alpha$. 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.

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 $\sin \alpha$. 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 fills up just slightly against the flow and slices through the air at a small angle of attack. If $\alpha$ 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 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 1. Aerodynamic lift and drag.](image)

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 $\alpha$, 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.

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and wing inertia are responsible for pitching the wing. Indeed, the observed tip-to-root direction suggests that aerodynamic force acts to accelerate the wing, starting from the root where the muscles act. The observed sequence, the drag on the wings is reduced, as is the power expended in flapping. But the reduction in drag on the two wings points in opposite directions, so the net force is essentially unaffected. In other words, the counterstrok ing 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.

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 counterstrok ing 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 evolved 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](http://dragonfly.tam.cornell.edu).

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