PERSPECTIVES: BIOMECHANICS

# Unsteady Aerodynamics

**Robert Dudley**

Insects are a conspicuous and abundant feature of life on Earth. With approximately 7000 new insect species described annually, entomologists regularly celebrate the taxonomic and morphological diversity of their favorite winged arthropods. Most of these taxa are fairly small by anthropomorphic standards (*1*, *2*) (see the figure). Some of the smallest beetles, for example, are the appropriately named nanoselliine ptiliids with body lengths on the order of 0.3 to 0.4 mm (*3*). Flight with small wings at such low Reynolds numbers (the ratio of inertial to viscous forces) is aerodynamically challenging—viscosity exerts a predominant influence on moving appendages, and wing flapping is often described as swimming in molasses. High wingbeat frequencies and novel wing morphologies are well known to be associated with flight under such viscous circumstances. But how exactly do small insects create the aerodynamic forces necessary to offset their body weight against gravity? By using a cleverly designed "robotic fly," Dickinson and coworkers (*4*) have now added substantially to our understanding of the aerodynamic mechanisms underpinning the flight of small insects (see page 1954). Because miniaturization has historically been a key process in the generation of the richness of insect species, elucidation of the associated physical means of flight can yield insight into contemporary arthropod diversity.

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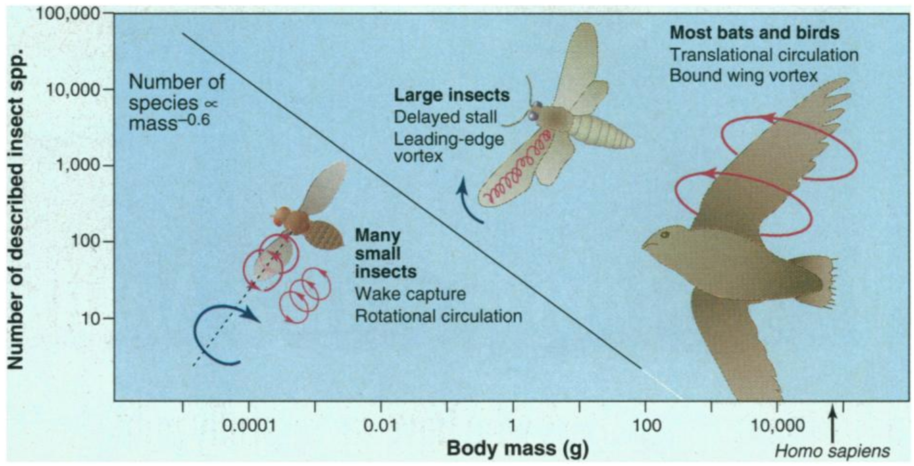
Traditional aerodynamic analysis of animal flight has followed conceptually the analogy of airplane wings moving at a constant speed and orientation (that is, angle of attack) relative to oncoming airflow. The spatial and temporal complexities of wing flapping are decomposed into consecutive instances of such steady-state airflow. As with the wings on airplanes, a single vortex circulating around the wing is presumed to generate aerodynamic lift. For many bats and birds, this steady-state analysis yields force balances consistent with those manifested by the animals themselves in free flight (see the figure). Lift production is progressively impeded at higher viscosities, however, and serious problems with the steady-state approach became evident when the estimated forces on flapping insect wings were shown to be insufficient to sustain hovering or even forward flight in some cases (*5*). Accelerations and changes in the wing's angle of attack during flapping badly violate the assumptions of steady-state flow, of course, and unsteady aerodynamic mechanisms must instead apply. Leading-edge vortices were recently shown to be generated on the flapping wings of hawkmoths, fairly large insects about the size of hummingbirds (*6*) (see the figure). High-speed rotation of the leading-edge vortex creates a low-pressure zone above the wing, and transiently increases lift production above that feasible through steady-state translation alone. For smaller insects, however, forces of viscosity progressively dissipate the energy of a leading-edge vortex, and additional mechanisms of force production must be sought.




**To fly a fly.** For large insects, lift forces derive from the presence of a leading-edge vortex that precludes stall and that transiently yields aerodynamic forces greater than those associated with steady-state flow. By contrast, flight of smaller insects is facilitated by rapid wing rotation at the ends of the down- and upstroke, and by taking advantage of vortices shed previously from the translating wing.

*Drosophila* has long served as a useful model in biology, and the new studies in this issue on insect flight aerodynamics (*4*) are no exception. Large-scale (25 cm) rigid models of *Drosophila* wings were attached to multiple motor drives that enabled flapping geometries similar to those of actual fruit flies. The apparatus was then immersed in a vat of viscous mineral oil to obtain Reynolds numbers equivalent to those experienced by small insects in air and thus nondimensional force coefficients on the model wings similar to those of hovering flies. A transducer at the base of one model wing enabled instantaneous forces to be measured throughout the flapping cycle. In most insects, reversal between the down- and upstroke motions of the wings is characterized by substantial rotation of each wing about its longitudinal axis. The flapping apparatus of Dickinson and co-workers faithfully replicated these rapid rotations for *Drosophila*, and revealed peaks of force production at the ends of each down- and upstroke. These forces were well in excess of those predicted by steady-state modeling, and substantially supplemented the forces of delayed stall produced during the translational period of each half-stroke. Thus, wing rotation and the associated circulation of air in an opposite rotational direction (see the figure) are a major force-producing mechanism in fruit flies and likely in many other small insects.

Intriguingly, the model *Drosophila* wings also produced substantial forces when transiently held stationary at the end of a half-stroke. This mechanism, termed wake capture, derives from airflow associated with the vortex shed from the wing during its previous stroke (see the figure). The lingering vortex wake is sufficiently strong and nearby so as to induce force-generating circulatory airflow around the wing.

Also important to force production is the relative timing (the phase relation) between wing rotation and translation. Along with the location of the rotational axis with respect to the leading edge of the wing, the relative phase of rotation was found to exert a strong influence on the magnitude of unsteady forces produced by rotational circulation and wake capture. The authors (*4*) point out that this sensitivity renders the timing of wing rotation an important parameter in the control

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of flight. Insects need change only by several percent the relative timing of wing rotation in order to alter substantially the magnitude and direction of forces on the wings, and thus to effect maneuvers. A general conclusion from this and other physical studies of flapping airfoils (*7*, *8*) is that unsteady aerodynamic forces are profoundly sensitive to the kinematic details of wing motion.

Wings of many insects are highly flexible about deformational axes largely determined by an often cross-connected network of hollow veins (*9*). Many tiny insects also express fringing hairs about the perimeter of the wing that likely enhance torsional and bending abilities. Use of flexible wing models in the robotic fly apparatus, however, only marginally altered forces during symmetrical wing flapping (*4*). Instead, the aerodynamic effects of wing flexibility may be most evident during maneuvers when these bilaterally paired locomotor appendages are activated asymmetrically. Much aeronautical attention has recently been focused on the construction of miniature flying machines, also known as microair vehicles. Can humans emulate technologically the elegance of a hovering hummingbird or the miniaturized maneuverability of a fruit fly? Wing flexibility, opposite wing interference, and the use of four rather than two wings (as characterizes the highly maneuverable dragonflies) (*10*) all potentially influence the magnitude of such unsteady force-producing mechanisms as rotational circulation and wake capture. Given this informative demonstration of the "robotic fly" for low–Reynolds number aerodynamics, the skies are now clear for functional evaluation of the wonderfully numerous evolutionary variants in insect design.

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PERSPECTIVES: MAGNETISM

# Small Is Beautiful

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Much effort is currently being devoted to the study of magnetic samples with at least two dimensions smaller than a micrometer (*1–3*). Many different approaches have been applied to the fabrication of such small magnetic entities, such as ultrahigh vacuum growth on carefully prepared surfaces, electrochemical growth on patterned substrates, and chemistry in nanosized vesicles. The motivation for this research is fundamental as well as applied. Fabrication and characterization tools can now achieve system sizes that allow testing and refinement of theoretical models. It is also important to understand the effects of reduced dimensions on future magnetic recording media.

Bulk magnetism is conventionally described by a hysteresis cycle, a map of magnetization versus field. Any point inside the cycle is accessible through a suitable field path. This macroscopic behavior results from many individual events that involve the creation and motion of magnetic domain walls or magnetization rotation. When the sample volume is reduced, the number of degrees of freedom also goes down. Classical micromagnetism theory has shown that each degree of freedom extends over a distance similar to the domain wall width. If a sample is smaller in all directions than the size equivalent to one degree of freedom, it falls into a single-domain state: All spins are now cou-

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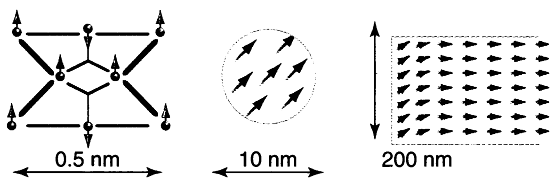


**All lined up.** Three systems representing magnetism in reduced dimensions: **(left)** the high-spin complex Fe8, in which only the iron atoms and their oxygen bridges have been drawn, **(middle)** a single-domain magnetic nanoparticle, and **(right)** the edge of a soft element of nickel with a thickness of 30 nm.

pled (see figure, middle panel). This sample is described by just one magnetization direction, and only a finite number of orientations are allowed at each field, such that the hysteresis cycle becomes almost empty. The first virtue of reducing the sample size is thus simplification.

The drawback is that, until recently, no one could see or measure the magnetic properties of such a single small object. However, recent years have seen the emergence of several techniques—magnetic force microscopy, microscopic superconducting quantum interference devices (microSQUID), and Lorentz force microscopy—that are sensitive enough to detect a single magnetic object of say 10 nm in diameter. In a recent paper, Majetich and Jin (*3*) show that Lorentz microscopy can be used to determine the magnetization direction in nanoparticles as small as 5 nm. MicroSQUID can now measure moments down to $10^4$ Bohr magnetons (the moment of a 6-nm iron sphere) (*4*), and developments are under way to improve that figure. Another property specific to nanometric scales is magnetotransport, as an electron keeps its spin orientation over the so-called diffusion length, which can reach tens of nanometers. Giant magnetoresistance and tunnel magnetoresistance are sensitive to the relative magnetization orientation of an electrode with respect to that of the counter electrode. This may enable direct read access to magnetic information (*5*). Moreover, tunneling spectroscopy can probe individual magnetization levels (*6*). Finally, magnetotransport might be the integrating link between the worlds of semiconductors and magnetism, with magnetism supplying the additional spin degree of freedom. Altogether, this palette of investigation tools has confirmed fundamental concepts such as single-domain states, superparamagnetism, and spin polarized tunneling. But new questions have also emerged. For example, nanoparticles of antiferro- or ferrimagnetic materials are prone to develop new magnetic orderings (*7*).

One very fundamental issue is the possible manifestation of a "macroscopic" quantum behavior of the magnetization in these small magnetic objects. Calculations suggest that quantum tunneling through an anisotropy barrier could become dominant over magnetic switching through thermally activated quantum tunneling below ~1 K. Last year, this effect was finally convincingly demonstrated in BaFeTiCo ferrite nanoparticles 10 to 20 nm in diameter below 0.3 K (*8*). A recent experiment (*1*) was performed on still smaller objects, namely high-spin molecular clusters (see figure, left). The well-known $Mn_{12}$ and