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Research Labs in Rochester, New York, demonstrated the potential for electroluminescence in devices of technological promise.[9] But films of such small molecules require vacuum deposition rather than the cheaper solution processing used for polymers.

Nobelists' careers

Born in 1936, Heeger earned his PhD at the University of California, Berkeley in 1961. He went to Penn in 1962, where he directed the Laboratory for Research on the Structure of Matter from 1974 to 1980. He has been a professor of physics at UCSB since 1982, and is director of its Institute for Polymers and Organic Solids. With Paul Smith, he co-founded UNIAX Corp in 1990 to develop commercial products based on electronic polymers. (DuPont acquired UNIAX in March.)

MacDiarmid was born in New Zealand in 1927 and received PhD degrees from the University of Wisconsin in 1953 and the University of Cambridge in 1955. He has been at Penn since 1956 and was named the Blanchard Professor of Chemistry in 1988.

Shirakawa, who was born in 1936, holds a PhD from the Tokyo Institute of Technology (1966). He spent his entire career at the Institute of Materials Science at Tsukuba University and retired at the end of March.

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Simple Mechanisms Help Explain Insect Hovering

> Experimental models and two-dimensional computer simulations of insect hovering provide insight that is missing in steady-state analysis.

The flapping motion of insect wings is qualitatively different from fixed airplane wings or even the rotation of helicopter blades. It's perhaps not surprising, then, that the quasi-steady-state analysis that works so well for aircraft predict for insects an amount of lift that's insufficient to keep them in the air.

Over the past two decades, the importance of the unsteady flows created by the flapping motion of insect wings has become better understood. Recently, Jane Wang of Cornell University has performed detailed two-dimensional (2D) computational fluid dynamics studies of insect hovering, which show that the vortices shed from the leading and trailing edges of the wings during the flapping motion can generate sufficient lift to support a typical insect's weight.[1] Wang's calculations join earlier experimental work on insect flight[2,3] in identifying the responsible mechanisms.

Stroke dynamics

When an insect is hovering, its wings execute what's called a "figure 8" stroke, which resembles the arm motions of a person treading water or the movement of the oar blade in a rowing stroke. This motion combines pitching and heaving, that is, rotational and translational movement, as illustrated in the figure on page 23. The plane of the stroke during hovering varies from insect to insect. It's nearly horizontal for bumblebees and fruit flies (and for people treading water), but is nearly 60° from horizontal for dragonflies.

Just as a spoon stirred in a cup of coffee produces swirls on either side of it, an insect's flapping wings produce vortices in the air (see the figure). The detailed behavior of the air surrounding the wings is governed by the Navier–Stokes equation, and the Reynolds number parameterizes the relative contributions from viscous and inertial effects. Insects are in an intermediate regime in which neither effect can be neglected. Consequently, the analysis of dynamics in this regime can be quite messy, and researchers have turned to empirical studies, models, and computers for insight.

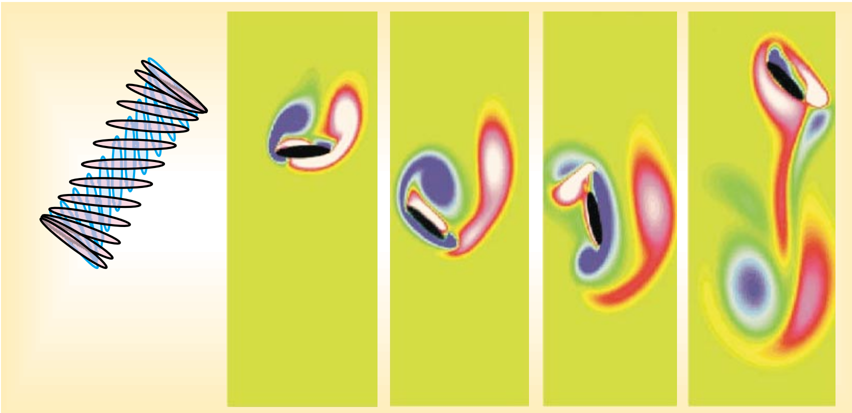
In 1996, Charles Ellington and coworkers at the University of Cambridge used smoke to image the airflows around a tethered hawk moth, and built a large-scale flapping model with the same Reynolds number as the moth to better study the dynamics.[2] They found that the vortex that forms on the leading edge of the wing spirals out away from the insect's body and toward the tip of the wing. This outward motion stabilizes the vortex and keeps it from separating from the wing during translational motion; such separation would produce stall and cause all the lift to be lost. These observations confirmed earlier work by Tony Maxworthy.[4]

Last year, Michael Dickinson and colleagues at the University of California, Berkeley, reported studies on their own dynamically scaled model insect, a robotic fruit fly, complete with sensors for monitoring the time-dependent aerodynamic forces.[3] In addition to spiral vortices during the wings' translation motion, the researchers found that the circulation induced by the wing rotation could produce significant lift, if the rotation was properly phased with the translational motion. They also proposed a third lift mechanism: wake capture, in which vortices created during one half-stroke interact with the wing to create lift at the beginning of the next half-stroke.

A minimal model

Computational studies of insect hovering face several challenges: nonlinear partial differential equations, dynamic boundary conditions, and a very narrow wing edge on which much of the key behavior depends. "It's no small feat to resolve vortex structures," notes Wang, who painstakingly compared detailed features in her simulations with existing experiments to ensure things were working before turning to insect hovering.

For her hovering computations, Wang chose a minimal model, to see if she could reproduce, in two dimensions, the essential elements of hovering flight. She considered a transverse cross section of the wing, modeled as an ellipse, perpendicular to the length of the wing. The center of the wing section moved up and down sinusoidally along the inclined stroke path. In addition to this translational movement, the angle of the wing section oscillated sinusoidally with the same period (see the figure). The



HOVERING SIMULATIONS for a two-dimensional cross section of a dragonfly wing. The schematic on the left illustrates the modeled path of the wing section over one full stroke. Purple ovals are the downstroke, blue ones the upstroke. The four panels on the right show the calculated vorticity generated by the wing (black) during the downstroke (first two panels) and the upstroke (next two panels). Blue represents clockwise vorticity; red, counterclockwise. The lift calculated from the 2D airflows in this model is sufficient to support the weight of a hovering dragonfly. (Adapted from ref. 1.)

model's parameters, including wing size and the stroke amplitude, plane angle, and period, were based on dragonflies.

Four snapshots from Wang's results for the vorticity created by the 2D wing are also shown in the figure. During the downstroke, counterrotating vortices grow at leading and trailing edges of the wing. The rotation at the end of the downstroke drives them together, and the resulting dipole moves downward. The downward momentum of the vortices is balanced by the upward lift on the wing. Wang concludes from her 2D results that the total lift from all four of a dragonfly's three-dimensional (3D) wings is sufficient to support the dragonfly's weight.

To some extent, the model is loaded for success, because the different mean angles of the wing on the downstroke and upstroke—due to the angle of the stroke plane angle and the phase and amplitude of rotation—ensure more upward than downward lift. "A cynic might observe that the principles of rowing have been rediscovered by direct numerical simulation," comments Geoffrey Spedding of the University of Southern California. "However, the kinematic parameters are not arbitrary. They have been guided by real data from real animals, and so the real achievement is to have demonstrated a very simple, but sufficient, physical model for adequate production of lift under realistic conditions."

The phasing between the pitching and heaving motions is important for controlling the pairing up of the leading and trailing edge vortices in Wang's simulations. This conclusion supports the findings from Dickinson's robotic fly. And for the short stroke amplitude of a hovering dragonfly, the wing changes direction before the vortices have a chance to separate during translation, so no 3D spiral flow is needed to stabilize the leading edge vortex.

Working together, Wang and Dickinson have begun comparing 2D computational results with empirical observations on model insects. There are some differences, but, says Wang, "The agreement is pretty good, surprisingly." Extensions to 3D simulations are under way by Wang in collaboration with Steve Childress and Charles Peskin at New York University's Courant Institute of Mathematical Sciences.

With the number of species of flying insects perhaps exceeding one million, it is perhaps too simplistic to assume that a single model of hovering dynamics is applicable to all of them. Ellington notes that the hovering of faster, more maneuverable insects, which tend to have inclined stroke planes and small-amplitude wing strokes, should be well described by a 2D model. For others, though, 3D flows will likely be important.

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