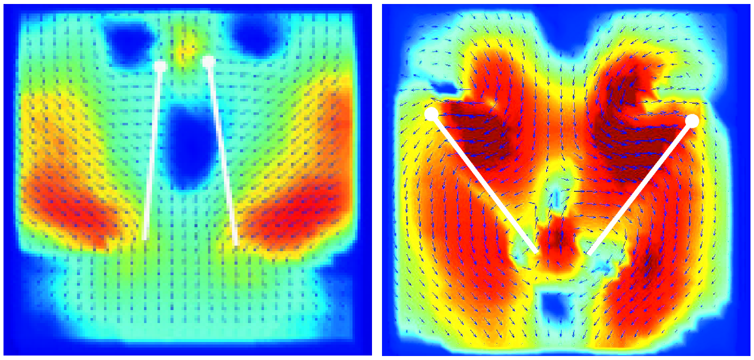
by Eric J. Lerner

Insect Flight Elucidated

Physics students, engineers, and others learned for years that "according to the laws of aerodynamics, bees can't fly," a fact often cited as an example of the limits of current scientific knowledge. Now new measurements of scaled-up mechanical models have shown just how bees and flies can fly. The new theory of small insect flight—developed by biologists Michael Dickinson and Sanjay Sane of the University of California, Berkeley, and Fritz-Olaf Lehmann of the University of Würzburg—could eventually lead to the development of mechanical insects with applications ranging from search and rescue to planetary exploration.



Particle-image velocimetry vector field of the fluid flow around insect wings as they clap together at the top of the stroke (left), and as they fling apart at the bottom of the stroke (right).

Conventional aerodynamic theory could not explain insect flight or the hovering flight of hummingbirds because at the small sizes and slow speeds involved, the viscosity of air overcomes conventional sources of lift. Reynolds numbers—the ratio of inertial to viscous forces—are very low, so flying becomes akin to hydroplaning in molasses: drag is large and lift is small. The flow of air over a curved wing, which supports planes, most birds, and large insects (such as butterflies and moths), just doesn't work for small insects. Yet these insects fly quite well.

Studies of air flow over the wings of small insects in the early 1980s gave the first clues to how they do fly. First, it became clear that small insects don't glide, because their wings do not supply enough steady-state lift. Therefore, transient forces developed during flapping must be the key to their flight. The first such force to be identified is generated by a vortex that forms on the leading edge of the insect wing when it is steeply tilted. Although such vortices form and then break away from the wing continuously, as long as the vortex is on the wing, the circulation produces upward pressure and thus lift.

But this leading-edge vortex, or "delayed stall" mechanism, does not create enough lift, and it wasn't clear how the insect could control the amount of lift generated. "The problem with these earlier studies is that they only studied the air flow, not the actual lift forces the wing developed. These had to be calculated from the observed air flow," explains Dickinson. To overcome this limitation, Dickinson and his colleagues decided to measure the forces, if not in actual insects, then in a scale model.

They built 25-cm-long Plexiglas wings to model the wing motion of the well-studied fruit fly, *Drosophila melanogaster*. To maintain the correct Reynolds number, they immersed the wings in mineral oil rather than air. Using electric motors, they drove the wings to both flap and rotate in the same way as real fruit-fly wings. Force sensors at the base of one wing gave direct measurements of the lift and drag forces at every point during the flapping cycle.

"Once we had the force measurements, we saw that the lift generated by the leading-edge vortex could explain some of the lift we observed, but not all of it," says Dickinson. Although the leading-edge vortex, because of the transitional motions of the wing, provided a fairly steady lift during both the upstroke and downstroke, there were additional sharp pulses of lift right before and right after each reversal of wing direction, when the wing was rotating rapidly.

Dickinson's team hypothesizes that these two pulses of lift are produced by two separate mechanisms. One is directly due to the rotational motion of the wing. When any object spins around a horizontal axis, it produces lift if the velocity is higher on top than on bottom. This Magnus force causes baseballs to curve, rise, or sink, depending on their spin direction. While the rotary lift has never been used by artificial aircraft (helicopters use the same steady-state lift as fixed-wing aircraft), insects do seem to use it. Calculations by Dickinson and his colleagues showed that the smaller pulse of lift, which comes just before each reversal of stroke direction, could be accurately predicted by this rotational mechanism.

The larger lift pulse, which occurs after each reversal, is due to the second mechanism discovered by the team. "The vortical flow generated by the wings in one stroke creates a wake, which increases flow velocity and therefore lift at the beginning of the next stoke," Dickinson says. This theory was verified experimentally by stopping the wing in midstroke and showing that the wing was still generating lift as the wake flowed past it. By recovering part of the energy lost to the wake, the insect improves its energy efficiency.

Not only do these two newly discovered sources contribute about one-third of the total lift, they provide almost all the control the insect exercises over its flight. Both the rational lift and the wake-capture lift are sensitive to the timing of the wing rotation relative to the time of the stroke reversal. If the wing rotates right before the end of the stroke, a net lift is generated, but if rotation occurs right after the reversal of direction, the net force is downward. A change in the phase of the rotation of just 8% changes the lift force by 67%. If a fly or other small insect provides more lift on one wing than on the other, it yaws and turns. Observation by the team of actual insects proved that the change in rotational timing occurs in just this way.

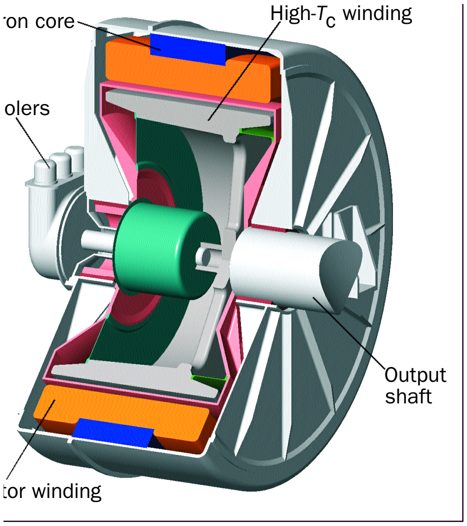
Although the new theory of insect flight is important in its own right, Dickinson and others are interested in applying it to the development of ultraminiature flying machines. "NASA would love to have exploration vehicles that are as tiny as insects," comments Dickinson, "and you can imagine how useful they would be in finding people after an earthquake."

The challenge is enormous, however. Not only must the aerodynamics of insect flight be understood better, but ultraminiature power sources are needed. So are tiny actuators that are as strong, weight for weight, as insects' muscles, and, probably most difficult, sensors and control systems that are no bigger than a fly's head. Because even supercomputers cannot yet duplicate the ability of a fly to deal with a three-dimensional environment, and because a single computer chip is far too large to fit in a fly, mechanical insects are probably a long way off. The new theory of insect flight is, however, a first step in that direction. Ω

High-T_C Motors

High-temperature superconductors are moving into more and more high-power applications. In June, the U.S. Navy's Office of Naval Research took this process a step further by awarding a contract to American Superconductor Corp. (ASC) of Westborough, Massachusetts, to design a 25,000-hp high-T_C motor for ship propulsion. This motor, the largest superconducting motor yet planned, is intended to power the DD21 generation of destroyers, which will replace the Aegis-class ships now in service.

American Superconductor already has a strong presence in large high-T_C motors. In April, it shipped the coils for a 1,000-hp motor being manufactured at Reliance Electric, part of Rockwell International, and it is now making the wire for a 5,000-hp Reliance motor (see *The Industrial Physicist*, 12/98, p. 16). The U.S. Department of Energy is contribut-



Design of a 25,000-hp high-T_c motor to power the DD21 generation of U.S. Navy destroyers.

ng $21 million to these two projects.

The motors use wire that is made from the superconductor compound BSCCO ($Bi_2Sr_2CaCu_2O_{8+y}$) and are cooled with liquid nitrogen. “The superconducting wire can carry 100 times the current density of copper wire (around 14 kA/cm^2), and the magnetic fields generated are twice as high as in conventional motors,” comments ASC spokesman Kevin Coates. This allows motors to be five times lighter and five times as compact as nonsuperconducting motors, which makes them of great interest to the Navy. In addition, the higher magnetic fields allow greater torque for the same size motor.

Although several major corporations are moving into high-T_c manufacturing, including Sumitomo and Seimens, ASC remains the leader in producing high-T_c wire. Production is now at 300 miles per year, about double that of any competitor. With the high-T_c-motor market already over $1 billion a year, more competition is likely. Ω

Nanotubes

Ordinary, low-temperature superconductivity has not yet run out of surprises, nor have nanotubes—filaments only a few nanometers wide composed of cylinders of carbon atoms. Recent experiments have shown that nanotubes, which can be insulators, semiconductors, or metals at room temperature, can become superconductors if they are suspended between two superconducting electrodes. The ultrasmall Josephson junctions thus formed may have unique possibilities as sensors.

Single-walled nanotubes (SWNTs) consist of a cylinder of helical-arranged carbon atoms and have a resistance of at least $h/4e^2$ (where h is Planck’s constant and e is the electron charge), or 6,500 Ω. By themselves, nanotubes are not superconducting at any temperature. However, a nanotube no more than a few micrometers long, like a piece of ordinary metal, can become superconducting if it is in contact at both ends with a superconducting electrode. A team of researchers from France, Germany, and Russia reported in the May 28 issue of *Science* that they had achieved such a proximity superconducting state for both single SWNTs and multiple-strand ropes.

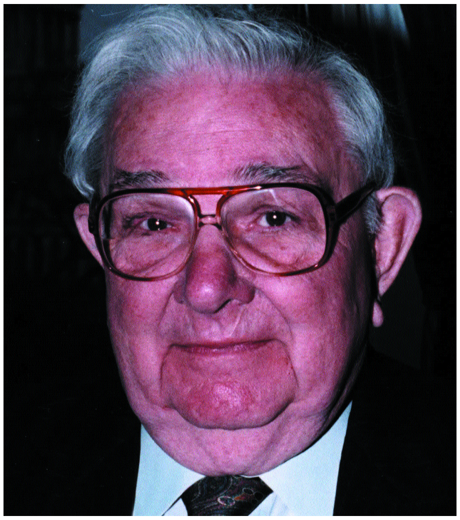
They strung nanotubes ranging in length from 300 to 1,700 nm between rhenium-gold or tantalum-gold contacts. At temperatures between 0.3 and 1.0 K, depending on the sample, the nanotubes became superconducting. This was not, however, what was most surprising.

The conventional theory of low-T_c superconductivity predicts that for proximity superconductors, the critical current (the maximum that can be carried by a superconductor) is $\pi\Delta/2eR$, where Δ is the superconducting energy gap and R is the normal or high-temperature resistance of the junction material. For the single-strand sample the researchers studied, this works out to only 2.5 nA. But the critical current observed was 100 nA, 40 times higher. Although this may seem small, it amounts to a current density of around 3 MA/cm^2, hundreds of times more than that of commercial high-T_c wire.

The high supercurrent isn’t easy to explain, but the researchers believe that—because of the quasi-one-dimensional character of the nanotubes—the tubes may have intrinsic superconducting fluctuations that are stabilized by the low-T_c electrodes. If the high supercurrents can be understood and predicted theoretically, the ultraminiature Josephson junctions could be turned into unique sensors for such uses as detecting extremely small amounts of heat energy. Ω

“Mr. Science” Dies

Rep. George E. Brown, Jr. (D-Calif.), earned the nickname “Mr. Science” as both an advocate and a constructive critic of science and technology. His death at age 79 on July 15 from an infection that developed after heart-valve replacement surgery ended a career that



helped shape the nation's science and technology policies for over thirty years.

Although he earned a degree in industrial physics from the University of California, Los Angeles, in 1946, Rep. Brown devoted his career to public service. He worked first for the City of Los Angeles in personnel, engineering, and management for 12 years and won his first elective office, to the city council of Monterey Park, in 1954,

Rep. Brown was serving his 18th term in Congress, where he was known for his intellect, integrity, compassion, and liberal views. He long served as a member of the House Science Committee and as its chairman from 1991 to 1994. Legislation that he championed included the establishment of the Office of Science and Technology Policy, the now-defunct Office of Technology Assessment, and the Environmental Protection Agency, as well as many bills relating to energy, technology, and the environment. He was a forceful voice for space exploration and international scientific collaboration.

"George was interested in technology for building the future, but to him, technology meant not just the physical infrastructure, but the mental and cultural infrastructures that support it," says Rick Borchelt, a former aide to Rep. Brown and now a senior research associate at the Vanderbilt University School of Engineering. "He was interested in the issue of how you build the world of the future in the broadest sense. His background as an industrial physicist helped him to visualize what that world might look like physically, but he was as equally concerned about what that world would look like culturally and intellectually." Perhaps that explains Rep. Brown's fondness for a particular genre of literature, science fiction. Ω