Lab Notes

"Things with a degree of order to them should be controllable to some extent."

Taming Turbulence

What do a helicopter rotor spinning, your heart beating, and a dolphin swimming have in common? Give up? They are all examples of unsteady, turbulent flow being exploited for useful ends. And while humans aren't nearly as adept at getting the mileage out of unsteady flow as nature is, we are learning something about it.

In the early 1970s, Garry Brown, then a senior research fellow, and Anatol Roshko, now the Theodore von Kármán Professor of Aeronautics, performed a series of landmark experiments that proved that one type of unsteady flow, shear flow, had a definite internal structure. A "shear flow" is like the traffic at an expressway on-ramp. Two streams of liquid, both flowing in the same direction but one traveling much faster than the other, merge. The flows can retain their separate identities for some distance downstream, separated by a "shear layer"—a turbulent region where the streams mix. Brown and Roshko discovered that the shear layer is dominated by a series of large eddies, or "vortices." These vortices swirl in the same direction; when a fast-moving stream on top joins a slow-moving stream on the bottom, for example, the vortices spin clockwise. They act as a series of roller bearings, taking up the velocity difference between the two streams while mixing them together.

Says Paul Dimotakis, then a graduate student and now professor of aeronautics and applied physics, "The classical view of turbulence at the time was that it was a random mess. I recall that close to a year was spent searching for troubles with the Brown-Roshko flow facility, trying to get rid of those vortices. It was so against the party line on what turbulence was supposed to be like. But after a year of trying, the conclusion was that that's what turbulence must really look like."

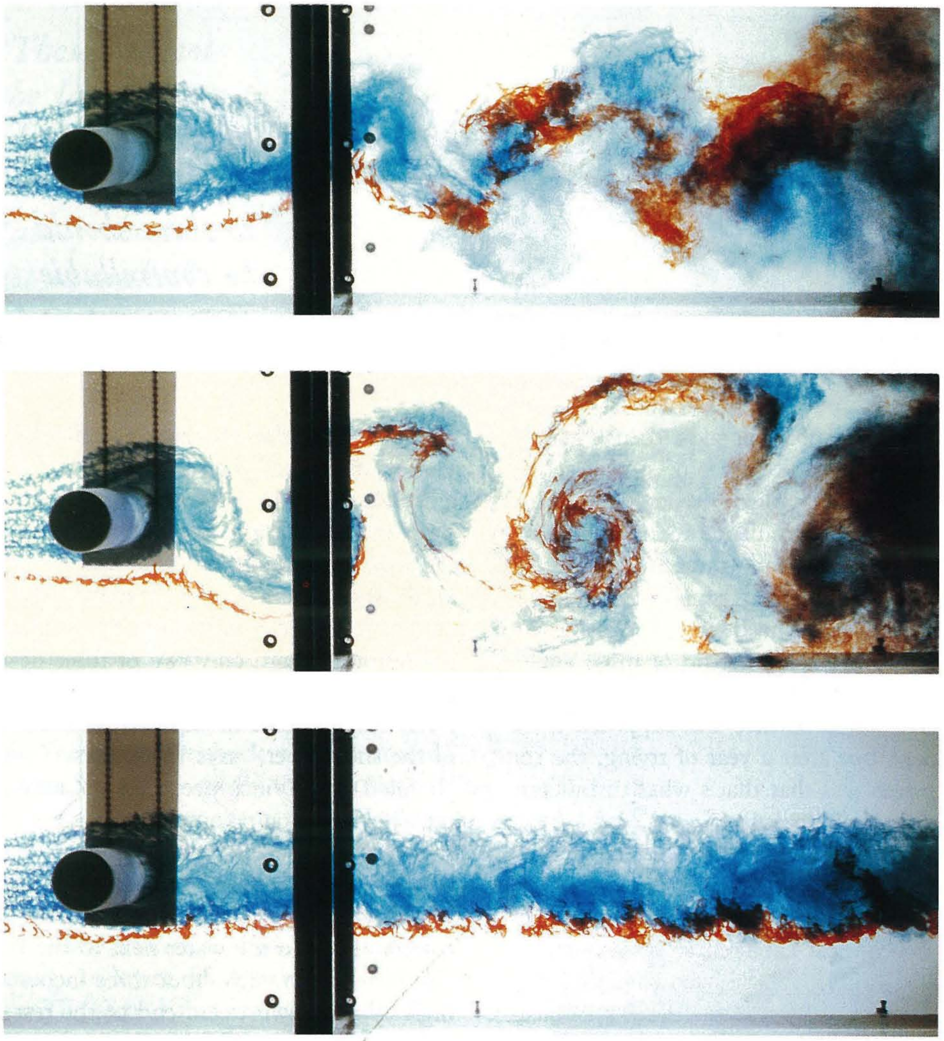
Brown and Roshko were in turn building on the work of Theodore von Kármán, founder of the Graduate Aeronautical Laboratories at Caltech (GALCIT), who had shown earlier that the wake behind a cylinder perpendicular to the direction of flow is dominated by a series of vortices with alternating spins. These vortices were thought to be peculiar to cylinders, however. Only after Brown and Roshko's discovery of similar vortices in shear-flow turbulence was it realized that order exists in all turbulent flows.

There was an important conclusion to be drawn from all this. Says Dimotakis, "Things with a degree of order to them should be controllable to some extent—if there is a semi-organized motion, you should be able to enhance it, inhibit it, or, better yet, program it. So if the flow has a tendency to form these vortices, in principle you can exploit that tendency to your own ends, like in judo, where you use your opponent's strength against him. But when we started trying to control turbulent flow 12 years ago, it was a very high-risk undertaking."

The work on shear layers continued, and Dimotakis and Manoocher Koochesfahani, now at Michigan State University, discovered that a gently moving airfoil (a winglike shape) placed in the shear zone where the two streams meet can have a profound effect. A pitching airfoil sheds vortices off its trailing edge at the frequency it is driven. By cycling the airfoil through only two or three degrees of pitch amplitude, "we got what I can only describe as explosive growth of the shear layer," says Dimotakis. "It filled the 20-inch-deep channel very rapidly. We don't know how much more we could have made it grow if its flow were unbounded." The shear layer, which was made visible by injecting colored dye into the water next to the airfoil, was normally about three inches high by the downstream end of the test section. (This work is usually done in wind tunnels, but "In the last decade, a host of new techniques have made water a particularly convenient medium. Our hydro lab is a unique facility, and we're very lucky to have it.")

Now Dimotakis is applying this technique to the type of turbulence where order was first discovered. He and graduate student Phillip Tokumaru have been experimenting with cylinder wakes. They have found that by rotating the cylinder on its axis, the wake's spread downstream can be narrowed or broadened by a large factor. Furthermore, when they narrowed the wake, they were able to reduce the cylinder's drag—its resistance to the flow around it—by as much as a factor of six.

"It seemed clear that if we oscillated the cylinder at something like its natural vortex shedding frequency we could strengthen the vortices," Dimotakis says. "It wasn't clear what would happen at much higher or lower frequencies."



Top: Normal wake behind a stationary cylinder.
Center: The cylinder is rotating to produce maximum dispersion.
Bottom: The cylinder is rotating to produce minimum dispersion.

So Tokumaru tried these other frequencies, and at the same time varied the amplitude of oscillation. He quickly discovered that the frequency affected the spacing between vortices, while the amplitude controlled the strength of each individual vortex. From there it was a short step to trying to program the vortices, setting the oscillation to launch the vortices with a spacing and strength that would cause them to approach each other downstream or to draw apart. And this, in turn, altered the rate at which the wake spreads.

Nobody is likely to try to narrow a motorboat's wake by fitting it with an oscillating cylinder, but Dimotakis hopes this work will address a number of fundamental phenomena of turbulent fluid flow. "We want to understand in detail exactly how the vortices leave the cylinder. That's what we're doing now. The separation of unsteady flow from a body to which it is attached is not a very well-documented chapter in fluid mechanics today, and here we have a highly controlled flow in which we can measure practically everything that needs to be known. We could use that information to develop criteria for computational models of separating unsteady flow, which we really don't know how to simulate very well now. And unsteady flow is paramount to so many natural phenomena. A heart valve works for a lifetime with no maintenance because the vortex it sheds helps close it with very little muscular expenditure—it just starts the motion. I've watched dolphins overtake a destroyer doing 30 knots while swimming at a 45° angle to its course. The dolphin was doing at least 40 knots with no trouble at all, just playing. It probably couldn't swim that fast if the flow was steady.

"We've only scratched the surface of being able to make flow and turbulence do what we want, instead of having to accept what it does. It could be exploited to make anything from supermaneuverable aircraft, to more efficient mixing and combustion devices, to better sailboats, to a whole slew of applications we really haven't yet imagined, because this behavior is so counter-intuitive."□—*DS*

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