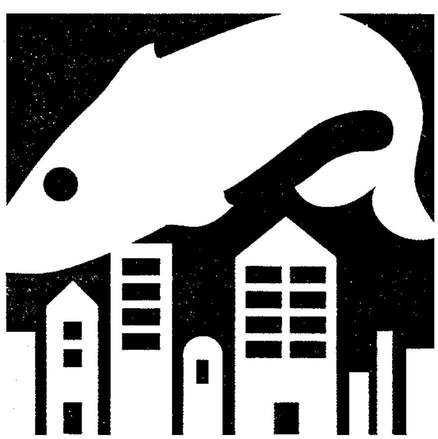
On a Fin and a Prayer

Frank **Fish**

People flying in airplanes invariably think of birds in flight and often draw analogies between the aerodynamic design of birds and that of aircraft. From Leonardo da Vinci to the Wright brothers, the study of bird flight and of the form and structure of birds had helped with the development of human flight. But birds are not altogether appropriate models for aeronautical design. Birds use beating wings to defy gravity and to propel themselves through the air, while airplanes use fixed wings for lift and engines for propulsion. To be truly analogous with aircraft, birds—or other flying animals—would have to generate their propulsion from a source other than their wings, and those wings would have to remain fixed.

Years ago, as the field of aviation was quite literally getting off the ground, researchers had looked at a different group of animal flyers with fixed wings as a possible analogue to the airplane. In the October 1908 issue of The Aeronautical Journal, between an article titled "The Probable Cause of the Explosion of Count Zeppelin's Airship" and another called "The Wright Bros' Flying



Machine," was one about the flight of flying fish. The article examined the steering and handling mechanisms of the fish for application to the airplane. But the subject is complex. A decade after Lindbergh flew across the Atlantic in the *Spirit* of *St.* Louis, researchers could not fully grasp how fish could fly above the surface of the ocean. Airplane designs were used to understand flying fish, rather than the converse.

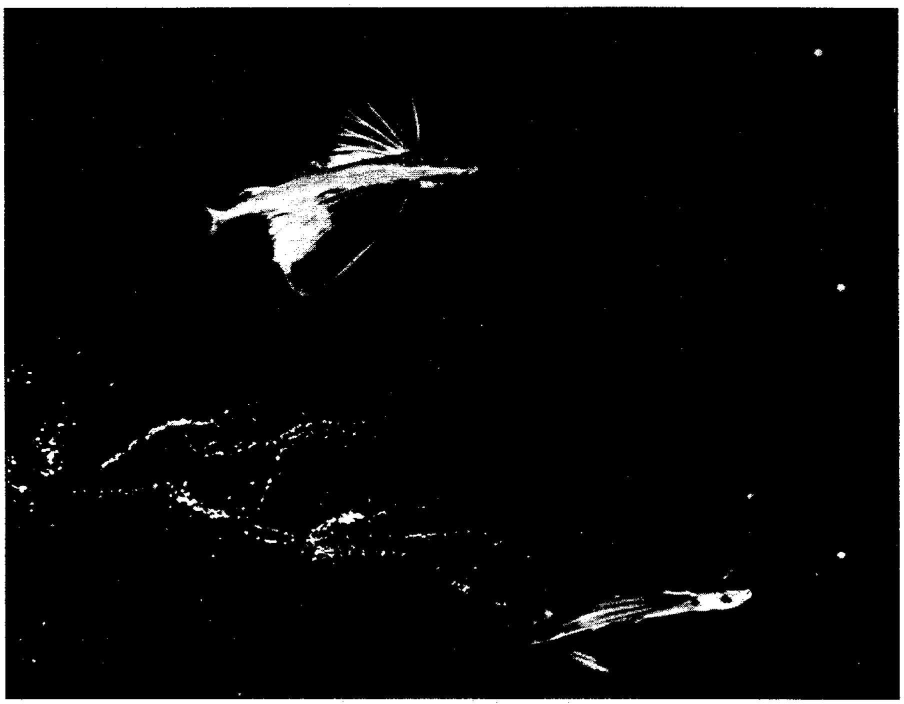
I first observed some flying fish from a boat off Key Largo in Florida. As the boat cruised along, the fish exploded from the waves produced as the bow sliced through the water. They took off in a direction perpendicular to the boat's course. With outstretched wings they sailed into the air about two feet above the water, traveling in a lazy banking arc. At the end of the flight they descended slowly to the surface of the water before falling back into the sea and disappearing into the swells as magically as they had appeared. Years later my interest in flying fish—unconnected in any way to my last name—was to emerge from my studying the variation in wing design among genera of flying fish and how such design influences aerodynamic capabilities.

How Fish "Fly"

Flying fish are part of a single taxonomic family known as the *Exocoetidae* and are most closely related to needlefish and halfbeaks. The family includes eight genera, eight groups, which frequent the tropical oceans of the world. Most are small, approximately six inches long, although the California flying fish can grow to 18 inches. The "wings" of flying fish are enlargements of the pectoral and pelvic fins, the paired fins of the body.

The pectoral fins are borne by the shoulder and located just behind the gills, and the pelvic fins are located toward the rear, on the underside of the body. When outstretched, both sets of fins furnish a broad surface to generate an upward lift force for flight. The aerodynamic shape of the pectoral fins is remarkably similar to that of some birds' wings. Like the curved upper surface on the wings of any bird or any commercial jetliner, the numerous fin rays supporting the wings of flying fish produce a curved or arched profile that helps generate lift for flight.

Flying fish are gliders, not true flyers like birds, bats, and insects, all of which fly by beating their wings. Researchers arrived at this conclusion only after much debate, because they had misunderstood the fluttering of wings from fish in flight. The wing flutter is not—as with birds—an oscillatory mechanism to generate lift, but the result of air rushing by a flexible structure. It is like a flag waving in the breeze.



To take to the air, a flying fish leaps from the water or rises to the surface continually beating its tail to generate propulsion as it starts to taxi. The taxiing run lets the fish accelerate at the water surface and build momentum for takeoff. Once the fish reaches its top speed of 20 to 40 miles per hour it spreads its elongate fins and becomes airborne. This action was captured beautifully in a series of high speed elecmc flash photographs taken at night by the father of stroboscopic photography, Harold Edgerton, of the Massachusetts Institute of Technology, and the noted ichthyologist Charles Breder, Jr., of the New York Aquarium.

The flight performance of these animals is impressive, with typical glides of 50 to 300 feet and flight times of 30 seconds. The fish can reach altitudes of 20 feet. There are accounts of them landing on the decks of ships. Scientists hypothesize that the fish can increase distance and time aloft by using updrafts from the windward face of waves. One report claimed that when flying into the wind a fish could travel over a quarter of a mile!

The trajectory of the glide by a flying fish is a flat arc, like that of some missiles. The French Exocet (the word means "flying fish" in French) is a missile that skims just above the water surface before striking its target, usually a ship. Such a sea-skimming weapon caught the world's attention in 1982 when the British ship HMS Sheffield was sunk by an Exocet launched from an Argentinean naval aircraft.

At the end of the glide when speed and altitude are decreasing, flying fish can either fold up their wings and fall back into the sea or drop their tail into the water and reaccelerate for another flight. This capacity for successive flights greatly increases the possibilities for air time. The record reported is 12 consecutive flights covering 1200 feet.

The key to this version of touch-and-go is the unique design of the flying fish tail. The usual tail fin of a modem bony fish has equal upper and lower lobes. The tail of a flying fish has an extended lower fin lobe. With the exception of flying fish, this type of fin is found only in the fossilized remains of ostracoderms, an early group of jawless fishes. The elongated lower lobe in flying fish lets the tail oscillations generate enough speed for flight without the entire body becoming submerged. The tail lobe works like an outboard motor powering a boat.

We don't understand very well why flying fish take wing. They may be escaping from predators. By leaving the water, they may be fleeing the jaws of death and confusing pursuers by splashing down in unpredictable places. They may also be saving energy. By moving through air, a less dense medium than water, they may be reducing the amount of energy they need for locomotion. Scientists think energy consewation may explain why dolphins leap from the water when swimming at high speed.

Flying fish can be divided into two morphologically distinct groups on the basis of their wing design—*Cypselurus* and Exocoetus. The first group has long broad wings derived from the pectoral fins, the paired fins at the shoulder. Enlarged pelvic fins aid these pectoral fins, representing as much as 25 percent of the overall wing surface. The Exocoetus have narrower pectoral fins than those of Cypselurus and the pelvic fins make up only about eight percent of the overall wing surface.

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The difference in wing design between Cypselurus and Exocoetus has been understood since 1930 when one researcher compared *Cypselurus* to an advanced biplane with a main (pectoral) top wing and a staggered (pelvic) under wing and Exocoetus to a monoplane with long narrow main wings.

Aerodynamics

To understand how the wing design of flying fish affects flight performance, let's examine the aerodynamics of gliding. As a glider moves through still air at a constant speed, it is acted upon by gravity and pulled downward by a force equal to its weight. That force in turn is resisted by an equal and opposite force directed upward. This upward aerodynamic force represents the balance between the "lift" force generated by the wings and the "drag" force resisting the movement of the body and wings through the air. The balance of these forces is all important in flight dynamics. The proportion of lift relative to drag is called the glide ratio. If drag rises relative to lift, the rate at which a glider loses height—its sinking speed—will increase. A loss of almost all lift is called stall. Anyone who has ever watched a paper airplane stop in mid-air before plummeting *to* earth is aware of stall.

To study how wing design affects flight performance, I examined the aerodynamic quantities of wing loading and aspect ratio, looking at the gliding ratio and the sinking speed. Wing loading is the weight supported by the area of the wings. Large flying fish with high wing loadings must fly faster to remain aloft with the same rate of sink as smaller fish with low wing loadings.

Aspect ratio is the square of the wing span divided by the wing area. A high aspect ratio means the wings are long and thin with high lift and low drag characteristics, wings that reduce sinking speed, like those of an albatross. Low aspect ratio wings are short and broad with low lift and high drag, like those of a flying squirrel.

Although Cypselurus and Exocoetus are similar in size, Cypselurus has lower wing loading and aspect ratio. The four broad wings of Cypselurus help with increased lift at slow flight speeds. The underside of certain species is flattened, increasing the total lifting surface of the fish. Exocoetus has two high aspect ratio wings, which means a substantial reduction of the drag on the wings for rapid flight. Although accurate flight speeds for the two groups are hard to come by—it is difficult to make measurements at sea without a fixed frame of reference and with variants in wind direction and speed—Cypselurus can glide farther than Exocoetus.

Exocoetidae and Other Flyers

How do the members of *Exocoetidae* compare to other flyers? Researchers traditionally group flying fish with all the other vertebrate gliders:

- "flying" frogs with their expanded webbing on the front and hind feet,
- Draco, the flying "dragon," with a flight surface formed from elongated ribs,
- "flying" geckos, warm weather lizards,
- a "flying" snake that can turn its body into a flight surface by forming a depression on its underside by drawing in its skin while the body is coiled into a triangular-shaped plane,
- mammalian gliders—flying squirrels, marsupial sugar gliders, and the colugo or "flying lemur"—in which the flight surface is a fur-covered membrane stretched out between the legs and the body.

Despite the superficial distinction of gliding, wing design and flight performance differ sharply between flying fish and other vertebrate gliders. Other gliders are restricted mainly to trees. They fly by descending from a position in the trees higher than where they will be at the end of their glide. Their flight surfaces are more like parachutes than wings. The very low aspect ratios of such flight surfaces slow the animals' rate of descent while preventing the onset of stall. The glide path is very steep. Flying fish have a shallow glide path at high speed. They begin and end their flight at the same level.

The fish have some design and performance characteristics that resemble those of flapping flyers, such as birds and bats. Wing shapes and glide ratios are remarkably similar between the two groups. But flying fish do not have adaptations for lightening the body—like pneumatic bones and air sacs—as birds do. To function underwater, the fish need a body density close to that of water for buoyancy and stability, and that need takes precedence over the advantages in flight of a lower body density. As a result, the wing loading is higher for flying fish than for birds. Flying fish must glide faster than birds to maintain the same rate of sink and to prevent the onset of stall.

Like all flyers, whether animal or machine, flying fish are inseparably linked to the physical constraints of wind and gravity. Despite these limitations, flying fish have aerodynamic designs that give them superior gliding proficiency in seemingly effortless flight. We must marvel at how a fish out of water can perform so gracefully.

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