Title:	An efficient swimming machine.
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Source:	Scientific American; Mar95, Vol. 272 Issue 3, p64, 7p, 1 chart, 3 diagrams, 4c
Document Type:	Article
Subject Terms:	ROBOTS
Abstract:	Reports that researchers at the Woods Hole Oceanographic Institution are developing a robotic tuna that moves through series of instinctive control and locomotory pattern. Technological innovations in the propulsion system of robotic fishes; Sensitivity against vortices; Delphine mystery; Mechanism of action of the vortices; Description of the robotic tuna developed. INSET: A tuna of aluminum and lycra.
Full Text Word Count:	4242
ISSN:	0036-8733
Accession Number:	9503032629
Database:	Business Source Elite

AN EFFICIENT SWIMMING MACHINE

Instinctive control of vortices lets fish swim the way they do. A robotic tuna has also managed it; boats and submarines may be next

Over millions of years in a vast and often hostile realm, fish have evolved swimming capabilities far superior in many ways to what has been achieved by nautical science and technology. Instinctively, they use their superbly streamlined bodies to exploit fluid-mechanical principles in ways naval architects today can only dream about, achieving extraordinary propulsion efficiencies, acceleration and maneuverability.

Dolphins, for example, dart through water with impressive grace and apparent ease, playfully bursting through the waves as they follow ships cruising at 20 nautical miles per hour (knots), or about 23 mph. Whereas records of the maximum speeds of fish are not always reliable and are often quite contentious, marine biologists have reported that yellowfin tuna caught on a fishing line can swim at speeds of at least 40 knots. The aggressive pike overcomes its prey with short bursts of acceleration that can exceed that of gravity by about 20 times.

Similarly, detailed observations have shown that fish that depend on aquatic agility for their survival can reverse direction without slowing down and with a turning radius only 10 to 30 percent of the length of their bodies. For comparison, maneuvering ships must reduce their speed by more than 50 percent, and their turning radius is at least 10 times larger than the corresponding, value for fish.

Nevertheless, and despite huge potential payoffs, relatively little work has been done to identify and apply the specific features of piscine propulsion that might benefit underwater and surface ships. Certainly the obstacle has not been lack of commercial motive; the immense amounts of cargo and passengers hauled by ship every year worldwide mean that even minute increases in efficiency would result in enormous savings in fuel. Increased maneuverability, moreover, could mean fewer accidents and greater safety for passengers, scientific instruments and the environment.

Such intriguing if distant possibilities were the topic of informal conversation with our colleagues at the Woods Hole Oceanographic Institution on Cape Cod, Mass., in the summer of 1989. In many places, the discussions would have been idle. But at Woods Hole, as at the Massachusetts Institute of Technology, the need for advanced and efficient propulsion systems is immediate. The two organizations are among several dozen around the world that are developing robotic, free-swimming craft that will one day explore ocean deeps, undertake military missions and help to maintain offshore oil installations. Extreme constraints on energy storage on board these so-called autonomous underwater vehicles demand propulsors more efficient than the propellers now used.

Developing them, however, would prove challenging. Replicating the performance of a fish by merely imitating its form and function would be impossible, because a smoothly and continuously flexing vehicle, with a fishlike body, is beyond the state of the art of today’s robotics. Still, the prospective rewards of the effort were irresistible.

Besides the authors, our team consists of Mark Grosenbaugh of the Woods Hole Oceanographic Institution, Dick K. P. Yue of M.I.T. and a number of our students and postdoctoral associates, most notably Knut Streitlien of City College of New York and David S. Barrett of M.I.T. Our effort complements biological studies such as Lawrence C. Rome’s study of power consumed by fish muscle, conducted at the University of Pennsylvania; Richard W. Blake’s measurements of the fast-starting performance of pike, carried out at the University of British Columbia; and research into the stability of fish swimming done by Paul W. Webb of the University of Michigan.

We started out by building simple foils that approximated the swish of a tail closely enough for us to reach new conclusions on the role of vortices in efficient swimming. Bolstered by these results, we built a fairly detailed replica of a bluefin tuna (Thunnus thynnus). The robotic, eight-link body and tail mechanism, which we called RoboTuna, let us further refine our findings and served as a prototype for the free-swimming model we are now fashioning.

Delphine Mystery

While planning our machines, we availed ourselves of the long trail of theoretical experimental and biological studies of how fish swim. In 1936 the British zoologist James Gray created a stir by calculating the power that a dolphin would need to move at 20 knots, as some were reported to do. Gray assumed that the resistance of the moving dolphin was the same as that of a rigid model and estimated the power that the muscles of the dolphin could deliver. His conclusion, known as Gray's paradox, was that the dolphin was too weak, by a factor of about seven, to attain such speeds. The inescapable implication is that there are flow mechanisms at work around the body of the moving dolphin that lower its drag by a factor of seven.

Almost 60 years after its formulation, Gray's paradox has yet to be proved or disproved conclusively. (The biological and hydrodynamic tests that would be needed for scientific certainty require accuracies beyond the state of the art in both fields.) Nevertheless, it has spawned numerous studies and has led to the accumulation of a substantial body of theoretical and experimental results related to fish swimming. Despite all the studies and experiments, however, hardly any useful technologies can be traced even indirectly to the principles of fish swimming. In some earlier efforts, despite promising theoretical foundations, fish-inspired mechanisms performed poorly. Given the remarkable abilities of fish, this seemed to us the true paradox.

If the fish is as efficient a swimming machine as is generally thought, its primary thruster--its tail--must also be quite efficient. One of the puzzles we found from previous work, however, was that experiments conducted with fishlike tails achieved disappointingly low efficiency. Our first task, therefore, was to find out why this was so.

In a motor-driven craft, efficiency is the ratio of useful power (thrust times forward velocity) divided by the power expended by the motor to drive the foil or propeller. Ideally, all the motor's power would be converted into propulsion, yielding a ratio of one. In practice, efficiency is always less than one, because some of the motor's power is wasted in wayward vortices and other undesirable turbulence as well as heat. For performance, the most important factor is the propulsor's efficiency at reasonably high levels of thrust; a device that is very efficient while producing only low levels of thrust is useless.

Any object in a flow, whether it is a wire in the wind or a swimming swordfish, creates a trail of spinning vortices. The wire obstructs the flow and leaves a wake, whereas the tail of a fish pushes water backward, establishing what is more properly known as a jet--a column of moving fluid that includes thrust-producing vortices. We became convinced that these Jet vortices play the central role in the generation of thrust, and we argued that their optimal formation would increase efficiency tremendously.

From previous studies we had done on the vortices produced by a wire in a stream of air, we were well acquainted with a fluid-dynamic parameter known as the Strouhal number. It is the product of the frequency of vortex formation behind an object in a flow and the width of the wake, divided by the speed of the flow. What the number indicates, compactly, is how often vortices are created in the wake and how close they are. Interestingly, the ratio remains constant at about 0.2 for a variety of flow conditions and object shapes.

Although the Strouhal number was invented to describe the wakes behind flow obstructions, the similarities between wakes and jets are such that we realized we could use the number to describe jets. For a swimming fish, we defined the Strouhal number as the product of the frequency of tail swishing and the width of the Jet, divided by the speed of the fish.

By analyzing data from flapping foils, we found that thrust-inducing vortices form optimally when the Strouhal number lies between 0.25 and 0.35. We anticipated that efficiency should be at a maximum for these values. Some preliminary experiments at the M.I.T. testing tank confirmed that the efficiency of a flapping foil does indeed peak when the Strouhal number is in this range.

With Grosenbaugh's collaboration, we subsequently analyzed a large amount of data collected about swimming fish. We found that fish of all sizes' from goldfish to sharks, swing their tail within the theoretically determined Strouhal number range of 0.25 to 0.35 [see top illustration on opposite page]. To show the formation of vortices and turbulence clearly, we conducted a separate trial in which we placed a small tropical fish in fluid that contained a suspension of tiny particles. By measuring the speed of the fish, as well as the frequency and the amplitude of its flapping tail, we calculated a Strouhal number of 0.30. Having satisfied ourselves of the number's importance in achieving high efficiency, we calculated its value for previous flapping-foil experiments that had reported disappointing efficiencies. None were even close to the 0.25 to 0.35 range. Returning to our laboratory with renewed zeal, we adjusted our foils to operate in this range--and measured efficiencies higher than 86 percent. In contrast, the small propellers used to drive underwater vehicles are typically no more than 40 percent effective.

Why Foils Are Efficient

What makes the high efficiency and high thrust of our foils possible is the manner in which the vortices are arranged behind the foil (or a fish's tail). The vortices become stronger as the load increases, but their rotational direction is always compatible with the desired direction of thrust, producing an efficient jet. A propeller, on the other hand, generates a long jet that rotates in the direction of propeller rotation, which is perpendicular to the direction of motion and needed thrust. All the power that goes into rotating this jet is wasted. The only way to minimize it and improve efficiency is to load the propeller very lightly, typically by giving it the largest possible diameter.

Another striking result from these experiments concerns the relation between efficiency and "angle of attack," the instantaneous angle between a foil's direction of motion and the plane formed by its leading and trailing edges. In our experiments, we found efficiency was at its peak when the largest angle of attack was between 15 and 25 degrees. This finding indicates the fundamental difference between steady airplane flight and flapping propulsion. The basic principles of fixed-wing flight require that, to avoid a stall, wings generally be kept to an angle of attack well below 15 degrees. Noticeable stall did not occur with the foil until the angle exceeded 30 degrees.

These results show that the criteria that indicate a stall for fixed wings do not apply to a flapping foil. True, what causes a stall in both cases is the sudden formation of uncontrolled vortices--above and behind the wings, in the case of aircraft, disrupting the normally smooth flow over them. With the flapping foil, however, vortices do not in and of themselves cause a stall. In fact, vortices--properly controlled and arranged--are essential to a foil's efficient operation, so it should be no surprise that they can be controlled over a wider range of angles to produce useful thrust.

These findings, along with those concerning the Strouhal number, suggest that a properly designed foil could be a very attractive propulsor for ships, motor yachts and underwater vehicles. Given its natural advantages and the fact that development of the proper motors and gears is well within today's technological capabilities, this foil might be the first fish-inspired technological application. The use of an even number of countermoving foils, properly positioned, could minimize unpleasant swaying or vibration. Of course, future shipbuilders would also have to address structural reliability, the hydrodynamic shapes of sterns and other variables.

Trick of the Tail

The coincidence of high thrust and efficiency is not the only advantage of a flapping foil. It also offers the possibilities of more flexible operation, more maneuverability and, most intriguingly, tempting opportunities for recapturing kinetic energy from a wake.

Fish instinctively exert precise and effective control of the flow around their bodies to extract energy from waves, turbulence and even their own wakes. They have also evolved ways of controlling the flow so as to enhance their turning and starting. The underlying principles are not unique to fish or even to flapping propulsion. A propeller mounted on a ship is somewhat more efficient than one tested in a tank, because the moving propeller recovers some of the energy from the wake. The phenomenon is routinely exploited by ship designers.

Fish, marine animals and their mechanical imitators, however, are much better suited to this kind of control. Frolicking and leaping in the wakes of ships for miles on end, dolphins are clearly recovering energy by positioning their bodies and flapping their tails appropriately, as Gray noted decades ago and as Neil Bose of Memorial University of Newfoundland has studied more recently. Fish can also recover energy from vortices in the ocean or even from vortices spun off from their own bodies.

The extraction of energy from unsteady flows using a stationary foil is called the Katzmayr effect, after the German engineer who first studied it, in 1927. In 1991 we explored a related phenomenon by placing a flapping foil some distance behind a cylinder in a stream. Rows of vortices generated by the cylinder moved toward the foil, which we could pitch and move sideways to encounter them in various positions. Systematic experiments confirmed that these adjustments could enhance or decrease efficiency.

Specifically, when the timing was right, vortices created by foil oscillations met incoming vortices spinning in the opposite direction. This effect weakened the vortices in the wake, resulting in the capture of energy by the foil and an in crease in its efficiency. This mode, obviously the most desirable for acceleration or high-speed swimming, is only one of three possible with such a setup. With a shift in timing, we induced vortices spinning in the same direction to meet and reinforce one another, causing a strong jet flow with no immediately obvious practical use. In the third situation, we paired counterrotating vortices to create mushroom-shaped eddies; if generated by a fish's tail, they would slow the creature down. Overall we could vary the efficiency of the foil by a factor of at least two, depending on the mode.

This one set of findings cast new light on a diverse set of observations. Photographs taken by the American engineer Moe William Rosen in 1959 of the flow behind a small, fast fish clearly show vortices from the creature's tail interacting with oppositely spinning vortices from its body. It has been reported as well that fish such as salmon and trout exploit oncoming vortices, such as those created behind rocks, to boost their swimming efficiency during their arduous upstream voyages. Aided by a continuous parade of such vortices, it is even possible for a fish's swimming efficiency to exceed 100 percent.

Vorticity control is also fundamental to the astounding transient performance of some fish, whose fast starts, sudden accelerations and maneuverings are far superior to those of ships and submarines. What makes this agility possible, in essence, is the ability to produce sudden, very large forces. Ships and submarines, on the other hand, exert no control over the flow around their hulls and move at a slow pace, their very large wakes with uncontrolled vortices creating enormous drag forces.

The control of vortices offers a novel solution. The idea is to produce favorable pressure gradients and then control them to optimize the response. Specifically, pitching and heaving a foil to a maximum angle and then back again produces a strong, sudden force, ideally suited to maneuvering and a fast start. The motion gives rise to a large initial vortex, followed quickly by another one spinning in the opposite direction. Sudden forward thrust, as well as a lateral force, results when the second vortex is briefly trapped between the first one and the surface of the foil.

This maneuver is exactly what a fast-starting agile fish does with its tail. Just before shooting off in some direction, its body flexes sharply, with the forward half of the body oriented at 60 to 120 degrees with respect to the ultimate direction of motion. Such orientation is necessary for the fish to compensate for the lateral force that accompanies the thrust.

A Motorized Bluefin

As useful as the flapping foils were in elucidating the hydrodynamics of fish swimming, the real proof of the principles, as well as the first step toward transferring the technology, lies in constructing an artificial fish that uses them to swim. About two years ago we had become confident enough to begin doing just that. We selected the bluefin tuna as our model because of its well-known ability to cruise but also because of its size, which would fit nicely in M.I.T.'s testing tank.

The body and tail of the 49-inch RoboTuna are flexed by an eight-link mechanism of anodized aluminum, driven by six brushless motors and an assembly of strings and pulleys [see box on these two pages]. A set of densely packed "ribs" and a special skin of reticulated foam and conformal Lycra allow smooth flexing and keep stray turbulence to a minimum. We attached the entire assembly to a carriage, on which we mounted all the motors and control and communication equipment. A single strut encloses the cables for data and power.

Several sensors along the side of RoboTuna record flow pressure, just as fish use their "lateral line" sense organs to detect pressure variations. Along with force and motion transducers, they permit detailed evaluation of swimming forces and propulsive efficiency. Simultaneous measurement of forces lets us directly link flow features to swimming performance and also control the flow to enhance the model's propulsion and maneuvering. Soon the side-mounted pressure transducers will enable us to experiment with closed-loop control of vorticity, so that RoboTuna, like its natural counterpart, will be able to move its tail in response to oncoming vortices and the flow around its body. We made the flow around the robotic fish visible by using either dyes or a laser beam that causes microscopic particles in the water to phosphoresce.

In a few months, another generation of RoboTuna will take shape. We expect to begin building a free-swimming model, borrowing on the technology developed for the existing robot. This successor will be used to develop skill more advanced technologies, based on our growing understanding of flow-control mechanisms, for possible application to commercial and naval vehicles.

More important, it will be a test bed for improving maneuvering and fast starting of vehicles using the fast generation and manipulation of large vortices. Such capabilities could prove invaluable even in oceanographic research, where underwater vehicles must sometimes operate in forbidding or confined environments. Near thermal vents, for example, temperatures can shoot up to hundreds of degrees Celsius in the space of a few feet or in a few seconds. In cluttered spaces, too, agility can sometimes stave off a collision or a catastrophic failure.

Nothing Like the Real Thing

The more sophisticated our robotic-tuna designs become, the more admiration we have for its flesh-andblood model. Aware that we will never match the perfection of design of the living creature, we strive instead to uncover natural, useful mechanisms optimized by millions of years of evolution. Once identified, a kind of reverse engineering may enable us to devise novel ways of using these mechanisms. In time, these biologically inspired creations may even outperform their natural antecedents in useful ways--for instance, in surveying a stretch of seafloor.

This goal is the guiding principle of the emerging science of biomimesis. By focusing research efforts and guiding the selection of parameters, details of the behavior and instincts of highly adapted, successful creatures can be a great asset in developing certain robots and other useful systems. Our project has required us to pose and answer fundamental questions about the mechanics of swimming.

For example, is fish swimming a simple perfection of hydrodynamic principles, constrained only by the mechanical limitations of muscle? Although the dolphin and the tuna are both fast and flex their bodies in similar ways while swimming, there are significant differences in the details of swimming as well. Are they both optimal solutions? If one is better than the other, is the superiority limited to certain situations? More Important, as far as we are concerned, is there an even better design than either of them for swimming?

These are among the questions we hope to address with our next robotic tuna. The state of the art in mechanical systems suggests that it will take our best efforts to approach the breathtaking abilities of its living model, but we will be patient. After all, in the span of a few years we are learning processes that took eons to develop.

A Tuna of Aluminum and Lycra

The body of a robotic tuna consists of aluminum links connected by hinges. Six motors, external to the robot, supply the power to mimic the undulatory swimming of a real tuna. Separate systems of pulleys and tendons transfer torque from each motor, while isolating the motion of the links. As it swims in the Ocean Engineering Testing Tank Facility at the Massachusetts Institute of Technology, the robotic fish hangs from a carriage (photograph, right).

DIAGRAMS: FISH OF ALL KINDS flap their tails to create vortices that produce a jet of high propulsive efficiency. Key parameters describing the jet are related in a ratio known as the Strouhal number, defined as the product of the frequency of tail flapping (yellow arrows) times the jet's width (purple), divided by the fish's speed (red). A Strouhal number between 0.25 and 0.35 is a hallmark of efficient swimming.

DIAGRAMS: FORCEFUL FLAP, followed in quick succession by another one in the reverse direction, produces a strong, sudden thrust well suited to pouncing on prey or a fast getaway. The initial flap makes a large vortex (1), and the second flap creates a different, counterrotating vortex (2,3). Strong forward thrust and a stray but manageable lateral force result when the two vortices meet and combine to create a jet and are pushed away from the tail, weakening each other (4).

PHOTO (COLOR): A strut supports the robot, encloses the tendons and conveys' control and sensor information.

PHOTO (COLOR): Links are connected by aluminum hinges, to which are affixed beams supporting ribs spaced one inch apart. The ribs and flexible beams hold the skin in place while allowing the body to flex continuously.

PHOTO (COLOR): A skin of foam and Lycra is smooth enough to eliminate wrinkles or bulges and their stray turbulence.

PHOTO (COLOR): Pulleys and tendons convey power from the motors to the links. Sensors on the tendons and in the fish measure input power, as well as external forces, pressure and velocity, and track vortices as they move along the robot's side.

PHOTO (COLOR): FISH ENCOUNTERING VORTICES senses the pressure variations of the spinning eddies as they move along its side. To capture energy from the vortices and boost its swimming efficiency, the fish instinctively times the flapping of its tail to create counterrotating whorls that meet and weaken the encountered ones.

PHOTO (COLOR): TAIL OF ROBOTIC TUNA spins off a trail of vortices of alternating orientation, made visible by dye: the tail swings to one side, creating a clockwise vortex, and then to the other, causing a counterclockwise one. Precise control of the timing and spacing of vortices is the main reason fish of all kinds swim as efficiently and skillfully as they do.

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by Michael S. Triantafyllou and George S. Triantafyllou

MICHAEL S. TRIANTAFYLLOU and GEORGE S. TRIANTAFYLLOU are brothers who independently became interested in fluid dynamics during their undergraduate years at the National Technical University of Athens. Both went on to earn master's and doctorate degrees in ocean engineering from the Massachusetts Institute of Technology, where they collaborated on studies of wakes created by nonstreamlined objects in a flow. For the work on fish swimming described in this article, they gratefully acknowledge the support of the Advanced Research Projects Agency, the Office of Naval Research and the Sea Grant Program at M.I.T. Michael now teaches in M.I.T.'s department of ocean engineering and is director of the Ocean Engineering Testing Tank Facility. George is professor of mechanical engineering and member of the Benjamin Levich Institute for Physicochemical Hydrodynamics of City College of New York. Remarkably, both of them take breaks from their work by going swimming.

Source: Scientific American, Mar95, Vol. 272 Issue 3, p64, 7p
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