HYDRODYNAMICS OF FISHLIKE SWIMMING

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Key Words vorticity control, biomimesis

Abstract Interest in novel forms of marine propulsion and maneuvering has sparked a number of studies on unsteadily operating propulsors. We review recent experimental and theoretical work identifying the principal mechanism for producing propulsive and transient forces in oscillating flexible bodies and fins in water, the formation and control of large-scale vortices. Connection with studies on live fish is made, explaining the observed outstanding fish agility.

INTRODUCTION

Marine propulsion and maneuvering has a long history of development and has already reached a level of maturity. This level is in some aspects satisfactory and in other aspects, particularly for transient motion, very limiting. Fast fish and cetaceans, on the other hand, move in water with great agility. They propel themselves through rhythmic unsteady motions of their body, fins, and tail; they offer a different paradigm of locomotion than that conventionally used in man-made vehicles. The view that the resulting unsteadiness in the flow is exploited by fish to their advantage is based on a series of studies demonstrating that they (a) generate large, short-duration forces efficiently, (b) coordinate rhythmic unsteady body and tail motion to minimize the energy required for steady propulsion, and (c) coordinate transient motion of the body and tail to minimize the energy lost in the wake during maneuvering.

Novel propulsion ideas based on unsteady flow control have emerged recently as progress in robotics, new materials, and actuators have become available. Unsteady propulsors and vehicles that emulate the motion of fish have been developed for technological application, using state-of-the-art technology and robotics and an understanding of how fish swim. In turn, from the development and testing of new systems, gains in understanding the principles of fish-like swimming have been obtained as well.
The basis for enhancing performance through unsteady flow control is the formation of large-scale vortices through body motion, the sensing and manipulation of these vortices as they move down the body, and the eventual repositioning through tail motion. These concepts constitute the essence of vorticity control.

VORTICITY CONTROL

Unsteady motion of a body and unsteady forcing in the flow can be used for efficient flow control (Tokomaru & Dimotakis 1991, Cortelezzi 1996, Koumoutsaksos 1999). The mechanics of flow body interaction are reviewed in Rockwell (1998). Unsteady propulsion may offer certain advantages when compared with conventional propulsors. In Gursul & Ho (1992) it is shown that unsteady motion of airfoils can cause a very high lift coefficient; and in Hoppe (1989) and Anderson et al (1998) foils are shown to produce propulsive thrust very efficiently.

Also, an oscillating foil can be used to alter and reposition oncoming vorticity (Koochesfahani & Dimotakis 1988, Cortelezzi et al 1997) and recapture energy contained in the eddies of an oncoming flow using vorticity control (Gopalkrishnan et al 1994, Streitlien 1994, Streitlien et al 1996, Anderson 1996).

The interaction of oncoming vorticity with a fin is a basic problem in the study of vorticity control mechanisms; its principles are of great importance to understanding fish swimming and maneuvering. As identified in Gopalkrishnan et al (1994), Streitlien et al (1996), and Anderson (1996), a harmonically oscillating foil may interact with oncoming large-scale vortices, which have a typical core size that is comparable with the foil chord, in three distinct ways to produce thrust. It is found that oncoming vortices

1. interact with foil-shed vorticity constructively, generating stronger vortices in the wake, arranged in the form of a reverse Kármán street
2. interact with foil-shed vorticity destructively, generating weak vortices in the wake, arranged in the form of a reverse Kármán street
3. pair with foil-shed vorticity of the opposite sign, generating a wake of vortex pairs, which drift away from the centerline, thus creating a wide wake.

Foil vorticity may be generated at the trailing edge, the leading edge, or both. The process of repositioning the oncoming vorticity is a crucial part of the interaction. As found theoretically (Streitlien 1994) and confirmed experimentally (Gopalkrishnan et al 1994), a foil may extract energy from the oncoming vortices when destructive interference with foil-generated vorticity is observed, increasing its efficiency substantially. Figure 1 (Gopalkrishnan et al 1994) shows the strong vortices created by an upstream-located D-section cylinder when it interacts with a foil in the destructive mode associated with maximum energy extraction. Flow is from right to left; vortices downstream from the foil are weak and drastically repositioned, compared with their original strength and location.
Figure 1 Oscillating foil manipulating oncoming vortices generated by an upstream located D-shaped cylinder. Strong vortices coming from right to left are repositioned and interact destructively with foil-generated vorticity, resulting in a weak reverse Kármán street in the wake (Gopalkrishnan et al 1994). The propulsive efficiency of the foil increases significantly.
Periodic forcing of a flow may alter the flow features considerably. Roberts & Roshko (1985) show that the vortex structure and mixing can be influenced through pulsing the flow. Taneda (1978) showed that the wake width behind a cylinder in an oncoming stream can be reduced through forced harmonic rotary oscillations of the cylinder. Tokomaru & Dimotakis (1991) considered the same problem as Taneda and found that rotary oscillation exerts a maximum influence on the flow when the frequency is close to the Strouhal frequency. Under proper conditions the wake width and, hence, the drag can be reduced substantially. Tokomaru & Dimotakis (1991) found that in unforced wakes the separation points move relatively little, and the natural instability of the flow redistributes the shed vorticity to create the large-scale patterns; whereas, in a forced oscillation, the separation points move substantially. Additional vorticity forms at the cylinder and is then released in the wake. Taneda & Tomonari (1974) and Taneda (1977) considered the effect of imposing a traveling wave motion on the flow around a flexible plate placed in a stream of velocity $U$. They found that turbulence in the boundary layer of the plate is suppressed when the speed of propagation of the traveling wave $c_p$ exceeds the free stream velocity.

OSCIllATING, THRUST-PRODUCING FOILS

A foil moving forward at steady speed and oscillating harmonically in a combination of lateral motion (heave) and angular motion (pitch) may produce thrust under proper parametric conditions. Thrust is produced when the time-averaged flow downstream of the foil has the form of a jet; however, if the flow is subject to drag force, it has the form of a drag wake. In either case, unsteady large-scale vortical patterns form in the wake, which has a shape affected by the parametric choices, as shown through visualization in Oshima & Oshima (1980), Oshima & Natsume (1980), Freymuth (1988), Koochesfahani (1989), Anderson et al (1998), and Kirby et al (1999). Two-dimensional flow studies show that the downstream flow may be characterized by the formation of a sinuous wake; or a wake that has either two large or four vortices per period. High propulsive efficiency is associated with the formation of two vortices per cycle, forming a staggered array of vortices resembling a Kármán street behind bluff bodies, but with the vortices rotating in opposite directions (reverse Kármán street).

A high-aspect ratio flapping foil has the following prime parameters: $(a)$ the amplitude of heave motion compared with the chord length; $(b)$ the feathering parameter (ratio of pitching angle compared with the maximum angle of attack induced by the heave motion); $(c)$ the phase angle between heave and pitch; $(d)$ the reduced frequency; and $(e)$ the relative position of the pitching axis. The Strouhal number and the nominal angle of attack may be used instead of the reduced frequency and feathering parameter. The nominal angle of attack is the maximum difference between the heave-induced angle and the pitch angle.
The Strouhal number is a nondimensionalized frequency, defined in analogy with bluff body flows as

\[ St = fA/U, \]

where \( f \) is the frequency of oscillation, \( A \) is the width of the wake (often approximated by the lateral total excursion of the foil), and \( U \) is the velocity of motion.

Although the reduced frequency provides a better measure of unsteadiness than the Strouhal number by comparing spatial wavelength of the flow disturbance with the chord length, the Strouhal number is a better parameter for characterizing the dynamics of wake flow. Both parameters are often needed because of the importance of both the unsteadiness in the foil and the dynamics of the wake (Luznik & Bose 1998). Ohmi et al (1990, 1991) studied the vortex formation in a translating and harmonically pitching foil at Reynolds numbers between 1,500 and 10,000 with mean incidence angle of 15° or 30°. At large incidences they found that the patterns in the vortex wake depend on whether the translational or rotational motion dominates the flow, which is determined primarily by the reduced frequency. They also found that when the flow is dominated by the rotational motion it is governed by a parameter proportional to the Strouhal number.

Triantafyllou et al (1991, 1993) proposed that optimum efficiency is obtained when the large-scale vortical pattern formation is compatible with the dynamics of the wake or, more specifically, when the frequency of foil oscillation coincides with the frequency of maximum amplification of disturbances, which is determined from the detailed linear stability analysis of the wake. A discussion of the relation between the disturbances after they have been rolled up into vortices and the produced thrust can be found in Streitlien & Triantafyllou (1998). Because the width of the wake is not a priori known, the lateral excursion of the foil is often used to define the Strouhal number. The optimum range of Strouhal number—between 0.25 and 0.35—is found for certain specific profiles used in Triantafyllou et al (1993); in other cases, different values may be obtained.

Fish swimming kinematic data showed that the nondimensional frequencies were close to the value predicted by instability analysis (Triantafyllou et al 1993, Rohr et al 1998). Figure 2 from Rohr et al (1998) shows the Strouhal number as a function of the Reynolds number for numerous observations of trained dolphins, showing good overall agreement between theory and experiment.

Dynamic-stall or leading-edge vortices form when the flow separates near the leading edge. Maxworthy (1979), Ellington (1984), Freymuth (1990), Rayner (1995), and Liu et al (1998) studied the aerodynamics related to the flight of hovering insects, and all groups concluded that unsteady flow mechanisms play a very important role. High values of lift coefficient were associated with the formation of a leading-edge vortex (dynamic-stall vortex), which for specific parametric combinations was subsequently amalgamated with trailing-edge vorticity. Reynolds & Carr (1985) discussed the basic mechanism that governs the generation of leading-edge vorticity also described by McCroskey (1982). Elling-
Figure 2 Strouhal number for swimming dolphins as a function of Reynolds’ number (Rohr et al 1998, with permission).

ton (1984) and Ellington et al (1996) also note the significant delay in stall caused by unsteady effects, as found earlier by Maresca et al (1979) for a foil at large incidences in steady flow, that are undergoing axial oscillations. The Reynolds number effect was found to be of secondary importance. Liu et al (1998) show clearly the three-dimensional formation and evolution of a substantial leading-edge vortex in a wing-simulating hawkmoth hovering.

Although leading-edge vortices are used primarily to provide a large lift force through the low pressure they induce, moderate formation of leading-edge vortices has also been associated with high propulsive efficiency, up to 87%, for moderately loaded foils in Anderson et al (1998). Figure 3 from Anderson et al (1998) shows the efficiency achieved in a flapping airfoil under various conditions of oscillation. Conditions for high efficiency are (a) amplitude of heave motion comparable to the chord length, (b) nominal angle of attack at about 20° and (c) Strouhal number compatible with the formation of a reverse Kármán street.

Three-dimensional effects in finite-aspect ratio foils become smaller for oscillating foils as frequency increases, compared with those of steadily moving foils. This is because of the formation of alternating-sign tip vortices (Cheng & Murillo 1984), which result in weaker induced velocities. The structure of vortices shed in the wake resembles vortex rings with adjoining backs, as first sketched in
Figur 3 Experimentally measured efficiency of a foil of chord \((c)\) flapping with amplitude \((h_o)\), frequency \((f)\), nominal angle of attack \((\alpha_o)\), pitch to heave phase angle \((\psi)\), as function of the Strouhal’s number \(St\). Curve (“case”) 1: \(h_o/c = 0.75, \alpha_o = 21^\circ, \psi = 75^\circ\); curve 2: \(h_o/c = 0.75, \alpha_o = 17^\circ, \psi = 105^\circ\); curve 3: \(h_o/c = 0.25, \alpha_o = 15^\circ, \psi = 90^\circ\); curve 4: \(h_o/c = 0.75, \alpha_o = 5^\circ, \psi = 90^\circ\); curve 5: \(h_o/c = 0.75, \alpha_o = 25^\circ, \psi = 90^\circ\); curve 6: \(h_o/c = 0.75, \alpha_o = 20^\circ, \psi = 90^\circ\); curve 7: \(\alpha_o = 10^\circ, \psi = 90^\circ\); curve 8: \(h_o/c = 0.75, \alpha_o = 30^\circ, \psi = 90^\circ\).

Lighthill (1969). Visualization has shown a pattern compatible with this picture although the reconnection details of the rings among themselves and the foil are complex, as shown in the flow visualization of Figure 4 (see color insert) (Hart et al 1992), obtained through air injection at the tip of a foil oscillating near a wall. The flow structure behind flapping foils in live fish is studied experimentally in Drucker & Lauder (1999).
STEADILY SWIMMING FISH

Fish swim with great agility, and certain species can reach high speeds. The relatively large-amplitude unsteady motion of their bodies is striking and intriguing to the observer, hence many studies addressed the subject of fish propulsion, summarized in Hertel (1966), Gray (1968), Lighthill (1969), Aleyev (1977), Blake (1983), and Videler (1993). Interest in explaining the mechanisms of fish propulsion peaked after Gray (1936) published a study that estimated that the muscular power of a dolphin is sevenfold less than the power needed to propel a rigid-straight model of its body at a speed between 15 and 20 knots, which Gray presumed to be the maximum speed achievable by dolphins (Gray’s paradox). Subsequent studies tried to explain or dispute Gray’s conclusion (Kramer 1957, Lang & Daybell 1963, Hoyt 1975, Fish & Hui 1991, Fein 1998).

Wu (1961, 1971a,b) and Lighthill (1960, 1970) investigated the propulsion characteristics of flexible two- and three-dimensional plates by using potential flow theory and linearized boundary conditions. Because of the elongated shape of most fishes, so that geometrical changes along the longitudinal (x axis) are much slower than those in the cross yz plane (the y axis is presumed to be in the directions of transverse motion, the z axis is in the nonflexing direction), the slender-body theory has dominated the theoretical modeling of fish hydrodynamics. In the slender-body theory it is assumed that the crossflow caused by the transverse motion of the fish’s body is approximately two-dimensional along planes perpendicular to the axis of the fish (in the yz plane). By further assuming unseparated flow the following expression is obtained for the transverse (lift) force per unit length (L) (Lighthill, 1960):

\[
L = -\left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x}\right) \left[a \left(\frac{\partial h}{\partial t} + U \frac{\partial h}{\partial x}\right)\right],
\]

where \(U\) is the speed of the fish, \(a\) is the local (two-dimensional) added mass per unit length, and \(h(x,t)\) is the vertical displacement of the backbone of the fish. If one assumes that shedding of vorticity occurs at sections along the contracting part of the body, then the following modified expression is obtained (Wu 1971b, Newman & Wu 1973):

\[
L = -a \left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x}\right)^2 h.
\]

Recent flow visualization work provides support for using the second expression for the posterior part of the body. Lighthill (1971) extended the slender-body theory to large amplitude motions. These seminal works provided a firm theoretical basis for studying fish swimming and gave insight into the basic swimming propulsive mechanisms.

Flow visualization, however, shows that the flow may differ qualitatively from the flow presumed in slender-body theory (Wolfgang et al 1999b). Depending on
the phase of oscillation, the flow may not be two-dimensional along \( yz \) (transverse) planes, and instead appears approximately two-dimensional along \( xy \) (longitudinal) planes, which resembles the flow over a flapping two-dimensional sheet, except near the body edges. Hence, quantitative predictions require numerical simulation, which provides more accurate results especially for the parameters associated with fish motion (Cheng et al 1991, Barrett et al 1999).

The details of the three-dimensional flow around fishlike bodies, especially the form and evolution of the vortical structures providing propulsive and maneuvering forces, were addressed only relatively recently. The potential flow theory (Lighthill 1970, Wu 1971b) assumes a frozen wake form, translating with the speed of the flow. The linearly unstable dynamics of the wake are known, however, to be very important in bluff body wakes in which they determine the frequency and wavelength of the dominant structure. By analogy, and by using the methodology developed by Triantafyllou et al (1986), the jet that forms behind self-propelled, actively swimming fishlike bodies is found to have characteristics largely dependent on the dynamics of the wake flow (Triantafyllou et al 1991, 1993) as described in the previous section. In a similar unsteady problem, Gharib et al (1994, 1998) and Rosenfeld et al (1998) found that in the transient formation of a circular jet flow through a piston, the leading vortex ring has reached its maximum circulation when the nondimensional “formation time” is approximately 4. The formation time is equal to \( Ut/D \), where \( U \) is the mean speed of the piston, \( t \) the time of formation, and \( D \) the diameter of the ring.

The presence of vorticity in the wake of a self-propelled body in a viscous fluid is a consequence of the need for a propulsive jet to counter the body drag. The dynamics of the free-wake vorticity play a prominent role in the selection of the frequency and form of swimming motion. Gray (1964, 1968) provides sketches of the flow around nematodes and a flow visualization figure of a live swimming eel, which demonstrates the importance of body-generated vorticity and the formation of a reverse Kármán street in the wake. A matter of some controversy is the presence of separated vorticity around the body of the fish. Rosen (1959) visualized the flow around and in the wake of a naturally swimming fish, showing large-scale vortices traveling near the body, well ahead of the peduncle region. Aleyev (1977) used dye visualization to show that such near-body vortices appear only when the fish swim in a shallow-depth tank. In deep water the flow remains attached; Aleyev noted the formation of a reverse Kármán street in the wake of fish.

Stamhuis & Videler (1995) used experimental particle image velocimetry to capture the flow dynamics around several live swimming organisms and to then analyze the energetic makeup of the wake. Anderson (1996) used experimental digital particle image velocimetry (DPIV) to visualize the wake behind a swimming Giant Danio (Danio malabaricus) and identified the active manipulation of shed wake vorticity to create a reverse Kármán vortex street (Triantafyllou et al 1996). Müller et al (1997) analyzed the wake of a swimming mullet (Chelon labrosus risso) using DPIV and concluded that the manipulation of the wake
structure resulted in high propulsive efficiencies. Figure 5 (see color insert) is a DPIV figure from Müller et al. (1997) showing clearly the flow about the fish body and the tail and the formation of a reverse Kármán street in the wake. Wolfgang et al. (1999a) compare experimental DPIV with numerical results, and they find that an inviscid numerical formulation, which satisfies the exact body boundary conditions, allows for the nonlinear evolution of the shed vorticity, and provides good description of the kinematics of the flow around the body and in the wake. A similar methodology was developed and used by Liu & Bose (1997) to treat flexible unsteadily operating foils.

Anderson (1996), Müller et al. (1997), and Wolfgang et al. (1999a) provide the following process of vorticity control used by fish: the body motion has the form of a wave traveling along the fish. This motion generates a flow that is characterized by spatially traveling waves of body-bound vorticity, when viewed at the longitudinal mid-height plane (intersecting at right angles the direction of transverse motion). Three-dimensionality of the flow (i.e. flow perpendicular to this longitudinal plane of view) is strongest near the upper and lower edges of the fish (Wolfgang et al., 1999b); this is a deviation from the assumptions of slender-body theory. The flow is, for part of the oscillatory cycle, closer to the flow that Wu’s (1961) theory provides for a two-dimensional sheet undergoing traveling waves. Figure 6 (see color insert) shows three transverse cuts (parallel to the yz axes), demonstrating that the flow is not two-dimensional within the yz plane, but contains strong features characteristic of two-dimensional flow in xy planes. The mix between longitudinal and transverse flow features varies with the phase of oscillation.

Figure 7 (see color insert) reinforces this view by showing two longitudinal cuts along the xy axes, demonstrating the persistence of two-dimensional–like flow from the mid-height plane (lower) to a plane at 20% of depth from the top (upper). This description is in agreement with the quantitative findings of Cheng et al. (1991), who show that the numerically predicted value for the transverse force lies between the estimates of the two-dimensional theory and the slender-body theory. Figure 7 (Figure 7 upper; see color insert) shows clearly the separation from the body and the tail interacting with oncoming vorticity to form the reverse Kármán street.

As the amplitude of body motion increases from head to tail, the bound-vorticity amplitude grows as well. As it reaches the point of maximum width, at about mid-length, vorticity at the upper and lower edges is shed in the wake, very weakly in the beginning and strongly as it reaches the peduncle region. The peduncle region is assumed for the purposes of this discussion to have a small transverse area. The details of shedding of vorticity depend strongly on the form of the body of the fish and the shape of the fins. Qualitatively, this flow separation provides support for Wu’s modified expression for obtaining the lateral force within the slender-body theory (Wu 1971b, Newman & Wu 1973).

In the peduncle area, free (shed) three-dimensional vortical structures have formed that interact next with the tail. The tail repositions vortices coming from
the fish’s left side to its right side, and vortices from the right to its left side. The interaction of body-generated vorticity with the tail resembles the control of oncoming vorticity through a fin, described in Gopalkrishnan et al (1994). A longitudinal planar cut of the resulting flow in the wake at the fish’s mid-height has the form of a reverse Kármán street, consisting of two alternating sign vortices per period, inducing a jet.

The shedding of vorticity by the contracting part of the body can also be seen in Liu et al (1997), who consider the computational fluid dynamics simulation of the swimming motion of a tadpole at Reynolds number 7200. Figure 8 (see color insert) from Liu et al (1997) shows the onset of separation from the edges of the body, whereas the wake consists of antisymmetrically rotating and positioned three-dimensional vortical structures. Their paper also describes the significant effect of the snout motion on the flow in the head region.

Ames’ (1998) flow visualization studies with live fish showed that shallow water effects cause stronger shedding of body-generated vorticity further upstream from the body, but the qualitative mechanics of swimming remain the same as for fish in deep water. Shallow-water fish visualization shows clearly that the vorticity control sequence applied by the fish through its tail manipulates oncoming vorticity. This reconciles the observations of Rosen (1959) and Aleyev (1977) and provides a unified explanation of the details of fish swimming.

TURNING AND FAST-STARTING FISH

Fast-starting and -maneuvering fish exhibit outstanding agility. Domenici & Blake (1997) review the literature on observed fast-starting kinematics of live fish, reporting for fast fish, such as the pike (Esox lucius), maximum accelerations in excess of 150 m/s² (Frith & Blake 1995, Harper & Blake 1991). The body of the fish is bent into either a C shape or an S shape, and then it is rapidly unwound in a traveling wave fashion. Weih (1972, 1973) extended Lighthill’s large-amplitude, slender-body theory to estimate the axial and transverse forces acting on a maneuvering fish using its body and fins.

Flow visualization studies have shown that, in fast-starting and maneuvering as in propulsion, the role of formation and control of vorticity is very important. Ahlborn et al (1991, 1997) show flow visualization caused by a fin forced to move in a double flip simulating the caudal fin motion of a fast-starting fish (i.e. motion to one side, shedding a vortex, followed by a reverse-direction motion, shedding a vortex of the opposite sign). This results in the formation of a pair of thrust-producing vortices. These experiments show that a time lag between flips enhances thrust production because it allows for the proper growth of the thrust-producing eddies.

Anderson (1996), Triantafyllou et al (1996), and Wolfgang et al (1999a) show experimental and simulation results of the flow around a maneuvering Giant Danio. Figure 9 (see color insert) shows DPIV flow visualization in a live Giant
Danio performing a C maneuver, compared with numerical prediction. The field of view is planar, intersecting the fish body at about its mid-height. We see the flow organized initially into two circular-like features, one centered near the tail and one near the head, as the tightening of the body into a C shape nears completion. These two features can be described as two body-bound vortices of opposite sign.

Subsequently, the tail begins to move to the fish’s left, and the counterclockwise vortex moves toward the tail region and is shed before the peduncle region. The shedding of vorticity before the peduncle region happens in the same way as described for a straight-swimming fish, but is more intense. The shed vorticity reaches the tail and is repositioned by the caudal fin, which interacts with vorticity shed at the trailing edge of the tail, ultimately moving in the wake. During the subsequent stroke of the tail, which is now moving in the opposite transverse direction (to the fish’s right), the clockwise vortex, initially seen near the head region, moves posteriorly, and sheds before the peduncle region. Then it is also manipulated by the tail and finally moves in the wake pairing with the previously shed counterclockwise vortex.

The result of the C-shape maneuver is a vortex pair, forming a local jet flow directed slightly downward and to the reader’s right, as shown in Figure 10, which summarizes the principal steps in the turning of the fish. The vortices in this pair are packets of counterrotating large-scale wake vorticity. The vortices comprising the jet have average nondimensional circulation 42% greater than the typical wake vortex strength for steady swimming of the Giant Danio (Wolfgang et al 1999b). The core radius of the jet vortices is more than double that of those produced in straight swimming. The vortex pair supplies the force needed to change the momentum of the fish.

The vortex pair that forms in rapidly turning fish is generated to a great extent by the body. The body-generated vorticity is repositioned by the tail and interacts

![Figure 10](image)

**Figure 10**  Body-bound and wake vorticity control during fish turning maneuver. Circled $L$ indicates a region of low pressure that is manipulated by the body and tail to reinforce the formation of the turning thrust jet (Wolfgang et al 1999b).
with tail-shed vorticity to form two precisely controlled vortices. The timing of formation, shedding, and position of the vortices is crucial to an effective maneuver. In fact, flow visualization shows the absence of any other (parasitic) shed vorticity, hence the absence of separation drag. A rigid streamlined body undergoing a similar maneuver would be subjected to considerable flow separation and resulting drag force. As in the case of a straight-swimming fish, the flow has a two-dimensional appearance except near the edges of the fish. Vorticity control by the tail may be described qualitatively in terms of two-dimensional vortex manipulation concepts, although the detailed flow picture and force estimation require a three-dimensional procedure.

The agility of fish is explained by the rapid generation of a vortex pair through body flexing and tail manipulation and by the absence of separation drag.

**BIOMIMETIC ROBOTS FOR HYDRODYNAMIC EXPERIMENTATION**

Biomimetics is an emerging field, using principles from living organisms to derive man-made mechanisms and vehicles that are capable of emulating the performance of animals. The field also has an impact on our understanding of the relevant mechanics of propulsion. In hydrodynamics highly accurate robotic
mechanisms are used to measure the power needed and forces generated, as well as visualize the flow around their external skin structure (Hover & Triantafyllou 1998).


Figure 12  Reduction in power needed by the actively swimming laboratory robot as percent of power needed to tow the robot rigid-straight, as function of Strouhal number \( St = f A / U \). Body flexes in traveling wave with maximum double amplitude at the tail equal to \( A \), frequency \( f \), moving at speed \( U = 0.7 \text{ m/s} \). The wavelength is chosen to be equal to 1.22 m, the nominal angle of attack at the tail is 15°, the phase between linear and angular motion at the tail is 90° (Barrett et al 1999).
Figure 13  Transverse averaged longitudinal velocity profiles at a given location, marked $a$, and at a particular phase of a plate, undergoing a wavy motion (see inset). The maximum amplitude $a = 0.032L$ ($L$ is the plate length), the wavelength is $\lambda = 0.4L$ and the phase speeds of the motion are $c/U = 0.0$ (circle), $c/U = 0.4$ (square) and 1.2 (triangle). $U$ is the speed of the incoming turbulent stream. The Reynolds number based on $L$ is 6000. The instantaneous (transversely averaged) friction velocity $u^*/U$ are, for $c/U = 0.0$: 0.055; for $c/U = 0.4$: 0.049; and for $c/U = 1.2$: 0.041.
Robotic mechanisms actuating flexible hulls are used as laboratory vehicles to obtain precise power measurements (Barrett 1996, Triantafyllou & Triantafyllou 1995, Barrett et al 1999) and to achieve the same outstanding agility in fast-starting and maneuvering observed in live fish, for technological use (Kumph & Triantafyllou 1998, Anderson 1998). The development of new materials and actuation mechanisms, such as shape memory alloys and conducting polymers, enhances the capability to emulate the performance of live organisms; they use actuators similar to the muscles and tendons used by the animals. Figure 11 (left) shows a laboratory robot, 1.2 m long, with an external shape in the form of a bluefin tuna (Barrett 1996), consisting of eight links. Figure 11 (right) shows a free-swimming autonomous robot 0.81 m in length, consisting of three independently controlled links, in the shape of a pike (Kumph & Triantafyllou 1998).

Barrett et al (1999) used a laboratory robot to study the effect of a fishlike body motion on the axial and transverse forces and hence the power required for swimming. The development of this high-precision, eight-link, robotic mechanism, which can emulate very closely the swimming of the tuna (Barrett 1996, Triantafyllou & Triantafyllou 1995, Wolfgang et al 1998), overcomes the difficulties associated with working with live fish because it allows the acquisition of detailed measurements of the forces on an actively controlled flexible body. Repeated precise measurements on the flexible robot have shown that, within a parametric range, the power needed to propel an actively swimming body at a Reynolds number of $\sim 10^6$ can be reduced by >50% compared with the power needed to tow the same vehicle in a rigid-straight configuration. Minimal required power is found for nondimensional parametric conditions that are very similar to those observed in live tuna (Dewar 1993, Dewar & Graham 1994). Figure 12 shows the reduction in required power in the actively swimming robot, as a percent of its required towing power and as a function of the Strouhal number, based on the tail fin excursion. There are two distinct peaks, one at a low Strouhal number, $\sim 0.13$, and another at a value of $\sim 0.25$. The shape of the curve is remarkably similar to the efficiency of a flapping foil as a function of the Strouhal number, shown in Figure 3 above.

In Barrett et al (1999) it is also found that if the body is subdivided longitudinally into three parts of roughly equal lengths, the front part absorbs 15%, the middle part 46%, and the rear part 39% of the total input power. This is in agreement with direct measurement of the power produced by the muscle of live fish along its length (Rome et al 1993). Rome et al concluded that the middle and rear parts of the fish produce most of the power and share it almost equally. This further confirms the important role played by the body in the generation of the propulsive force, as also revealed through flow visualization.

The robotic fish study was conducted at near-transitional Reynolds numbers, in which flow can be fully relaminarized through traveling-wave motion as shown in Taneda & Tomonari (1974) and Taneda (1977). Zhang (1999) studied, through direct numerical simulation, the three-dimensional flow around a two-dimensional plate undergoing traveling-wave–like oscillations at $Re = 6,000$ in a steady
oncoming turbulent flow of velocity \( U \). Turbulence intensity was 5\%, whereas the speed of traveling waves \( c \) could be varied arbitrarily. Zhang found that turbulence is reduced significantly when \( c/U > 1 \). Figure 13 shows the instantaneous shape of the plate (lower), with the amplitude quadratically increasing in the direction of flow (left to right). Three average-velocity profiles in the boundary layer are shown in location \( a \) (defined in the inset). The profile for \( c/U = 0 \) has the characteristic shape of a turbulent profile; for \( c/U = 0.4 \), it has undergone a small change, but at \( c/U = 1.2 \) it has largely laminarized. As also found in Barrett et al (1999), Zhang found that the power needed to propel the foil is minimum at \( c/U = 1.2 \). Similar conclusions are reached in the experimental work of Techet (1999) and Anderson et al (1999), who performed DPIV flow visualization in the boundary layer of the laboratory tunalike robot, shown in Figure 11, at \( Re = 7 \times 10^3 \); as well as in the boundary layer of live fish.

ACKNOWLEDGMENTS

The authors received financial support from the Office of Naval Research contract N00014-96-1-1141 (monitored by P. Purtell, T. McMullen, and J. Fein) and the Sea Grant Program under Grant NA46RG0434.


LITERATURE CITED


Hoppe KG. 1989. The dynamo-elastic oscillating foil propeller. Schiff Hafen 5:54–61
Woods Hole Oceanographic Inst. Joint Program, Cambridge, MA
Figure 4 Photograph of tip vortex formation downstream of an oscillating hydrofoil (right) visualized by injecting air at the tip of the hydrofoil near the trailing edge. Injected air is entrained into the low-pressure core of the tip vortex tracing the complex structure of the vortex formation. The tip vortex can be seen connecting the shed spanwise vortices resulting in the formation of an intricate vortex chain ($Re = 1.5 \times 10^5$, angle of attack $5^\circ$, oscillation amplitude $15^\circ$, reduced frequency $\pi fc/U = 5.2$) (Hart et al 1992). Photograph from Hart et al (1992), provided by Prof. Hart.
Figure 5 DPIV flow visualization in the vicinity of a straight-swimming mullet. Arrows represent velocity in meters per second (Müller et al 1997). From Müller et al (1997) with permission from the Company of Biologists Ltd.
Figure 6 (below and following page) Flow visualization along planes perpendicular to the long axis of a straight-line–swimming Giant Danio. Longitudinal locations of the planes are shown on the outline of the Giant Danio (top). Streamlines (black) are superimposed on a dense velocity vector grid. Velocity vectors scaled in size by velocity magnitude and scaled in color by longitudinal vorticity $\omega_x$ contours (range: $-0.1 \text{ s}^{-1}$, $0.1 \text{ s}^{-1}$). Red vorticity indicates clockwise rotation; blue vorticity indicates counterclockwise rotation; green regions denote irrotational flow. A primarily longitudinal pattern is visible at the head (cut AA, below). The midbody downstroke produces primarily a transverse flow (cut BB, top, next page). As the contraction region reverses undulation direction, longitudinal streamlines to the left of the body and fins combine with a weakly transverse flow from bound vorticity generated upstream (cut CC, bottom, next page). From Wolfgang (1999).
**Figure 7** Flow visualization along xy planes, containing the long axis and direction of transverse oscillation of a straight-line–swimming Giant Danio of depth (D). *Top*, z/D = 0.2 measured from the top; *bottom*, z/D = 0.5. Streamlines (black) are superimposed on a contour plot of the vertical vorticity $\omega_z$ component in the plane (range: $-0.5$ $s^{-1}$, 0.5 $s^{-1}$). *Red* vorticity indicates clockwise fluid rotation; *blue* vorticity indicates counterclockwise rotation; *green* regions are irrotational (Wolfgang et al 1999b).
Figure 8 Views of a virtual tadpole at $Re = 7200$. Isovorticity contours are illustrated with *white lines* at the base of the tail and at the mid-tail; wake vortices are shown in *green*. (A) The tail in a C-curve posture. (B) The tail in an S-curve posture (Liu et al 1997). From Liu et al (1997) with permission from the Company of Biologists Ltd.
Figure 9 Flow visualization during the 60° turning maneuver of a Giant Danio. Top, DPIV measurements of live fish; bottom, simulation results at the mid-depth plane corresponding to the same time instant. In-plane velocity streamlines (black) are superimposed on a dense velocity vector grid. Velocity vectors scaled in size by velocity magnitude and scaled in color by vertical vorticity $\omega_z$ contours (range: $-20 \, \text{s}^{-1}$, $20 \, \text{s}^{-1}$). Red vorticity indicates clockwise rotation, blue vorticity counterclockwise rotation, and green regions are irrotational (Wolfgang 1999).