TECHNICAL NOTE

Advantages of Natural Propulsive Systems

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ABSTRACT

The screw propeller has been the mainstay of marine propulsion, but new developments in biomimetic propulsion can provide advantages in terms of speed, maneuverability, efficiency, and stealth. The diversity of aquatic animals provides designs for drag-based paddling and lift-based oscillatory hydrofoils that can be incorporated into engineered propulsive systems for enhanced performance. While the screw propeller will remain the prominent propulsive device, the choice of alternative biomimetic propulsive systems will be dependent on particular applications, where the specifications dictate improved performance criteria.
Keywords: biomimicry, speed, maneuverability, stealth, efficiency

In recent years, engineers have looked to biomimetic solutions for application to marine systems (Fish & Kocak, 2011). In particular, propulsive systems by animals hold the promise for improved performance by machines and vessels operating in the ocean environment (Bushnell, 1998; Fish & Rohr, 1999; Triantafyllou & Triantafyllou, 1995). Naval interests have been concerned with improvements to propulsive systems with regard to speed, maneuverability, efficiency/economy, and stealth, including silence and wakelessness (Bushnell, 1998; McKenna, 2011; Shaw, 1959). Although the screw propeller has been considered more effective compared to other forms of propulsion for over 160 years (Carlton, 2012; Larrabee, 1980), it has certain limitations with respect to the list of performance attributes, which are of interest for naval operations. Screw propellers have problems related to cavitation, a small operational range of maximum efficiency, reliance on control surfaces maneuvering, and a detectable and identifiable acoustic signature. The propulsive systems of animals may alleviate some of these limitations.

Motion through water requires the development of thrust from a propulsor by the acceleration of fluid into a wake to counter the resistive drag and added mass forces. To generate thrust and effectively move in water, aquatic animals have evolved a diversity of propulsive mechanisms correlated with their biological role, evolutionary history, and association with the aquatic environment. To locomote in water, these animals must produce hydrodynamic thrust by acceleration of the water from their body and appendages while simultaneously reducing the resistance to their motion. Because of their swimming capabilities, aquatic animals have recently gained wide attention as models for underwater vehicles (Anderson & Chhabra, 2002). The mechanism of propulsion used by animals is considered a viable alternative to traditional marine propulsors. Indeed, aquatic animals are considered to be superior in their propulsive abilities compared to technologies developed from marine engineering (Anderson & Chhabra, 2002; Fish et al., 2011; Triantafyllou & Triantafyllou, 1995).

The focus of this technical note is concerned with how thrust is generated by the various propulsive mechanisms exhibited by animals. A survey of the biomechanical and hydrodynamic mechanisms of biological propulsive systems will permit identification of innovative mechanisms that may be transitioned to manufactured designs. In this regard, the examination of animal propulsive systems will be confined to high Reynolds number, inertial-based swimming. This mitigates scaling problems inherent in application of small, viscous-dominated systems to large-scale systems associated with current technologies and tasks. With the exception of jet propulsion by cephalopods (e.g., squid, octopus), the majority of analysis on swimming and related hydrodynamics of undulatory bodies and oscillatory appendages has been performed on fish.

Propulsive Forces

The diversity of propulsive surfaces and structures can be classified with regard to the forces generated. For animals, the pertinent forces are pressure drag, acceleration reaction, and lift (Fish, 1996; Webb, 1988; Webb & Blake, 1985). These forces are generated actively by motion of the propulsive surfaces (e.g., fins, flippers, flukes, legs) or from flow ejected from volumetric contraction (i.e., jet propulsion).

Pressure drag is a resultant of the asymmetry of the fore and aft flow around an appendage. This asymmetry creates a pressure difference, which is the basis of the drag and can be used for propulsion. Drag-based propulsion is associated with paddling. The paddle is unstreamlined with a broad distal end, thereby increasing propulsive efficiency by affecting a large mass of water (Alexander, 1983). In animals, the stroke cycle is divided into power and recovery phases (Fish, 1996; Webb & Blake, 1985). During the power phase, the posterior sweep of the appendage generates drag, which provides an anterior thrust to the animal. The recovery phase repositions the appendage. To prevent an increased pressure drag on the appendage that will negate the thrust generated, the appendage is collapsed or feathered. Examples of drag-based swimmers include labriform fish, frogs, turtles, ducks, and semi-aquatic mammals. Paddling is typically associated with slow surface swimming and precise maneuverability.

Acceleration reaction results from changes in the kinetic energy of water accelerated by action of the propulsive body structure (Daniel, 1984; Webb, 1988). The acceleration reaction differs from drag in that (1) the acceleration reaction is directly proportional to the volume of an object, while drag is proportional to the surface or cross-sectional area, and (2) the acceleration reaction depends on changes in velocity of an object, resisting both acceleration and deceleration, while drag depends on the instantaneous velocity of the object, resisting acceleration but augmenting deceleration (Daniel, 1984). Animals use the acceleration reaction when swimming by undulation by passing waves down the body or through fins (Daniel & Webb, 1987; Webb, 1975, 1988). Flattening of the undulatory surface enhances the magnitude of inertial effects (Lighthill, 1969).

Acceleration reaction is used also for jet propulsion (Daniel, 1984), which is a means of propulsion used by cephalopods (squid, octopus), jellyfish, scallops, salps, and frogfish. Thrust by jetting results from the forceful expulsion of a mass of water from an internal cavity. As the fluid is not heated to rapidly expand its volume as it occurs in conventional jet engines, jetting animals are required to have a body that can retain a large quantity of water prior to expulsion. The water is expelled through a constricted aperture. This constriction permits a longer duration jet with a higher velocity relative to the velocity of the organism (O'Dor & Webber, 1986). In addition, some jetting animals (e.g., squid) can direct the aperture to vector the thrust of the jet for maneuvering control. Jetting over extended periods involves pulsatile flow, as the contraction of the cavity responsible for ejecting the fluid must be refilled.

Appendages, which are used to generate lift-based forces for propulsion, are relatively stiff hydrofoils. To maximize lift, the hydrofoil has a crescent, winglike design with high aspect ratio (Lighthill, 1969; Webb, 1984). This shape provides the hydrofoil with a high lift-to-drag ratio and high propulsive efficiency. As the hydrofoil is oscillated, the angle of attack is controlled (Fish & Lauder, 2006; Lighthill, 1969). The angle of attack is generally a small angle corresponding to the deflection of the hydrofoil from the flow. Lift arises from asymmetries in the flow. The asymmetry generates a pressure difference between the sides of the hydrofoil with a net force normal to the incident flow. Lift is generated continuously with a steady flow. Although the hydrofoil produces some resistive drag, it is small compared to the lift. Tuna, sharks, sea turtles, penguins, cetaceans, sea lions, and phocid seals use lift-based propulsion.

Screw Propeller Versus Natural Propulsion Systems

Within the immense diversity of aquatic animals is a variety of solutions to effect locomotion through water. The varied morphological features and their structural organization and kinematics present a rich resource of novel designs that may be incorporated into propulsive systems. Because both engineered propulsive systems and animals must contend with the same physical laws that regulate their design and performance, there are instances in which the propulsive systems of animals can be superior to the performance of machines. As stated above, there are four parameters (speed, maneuverability, efficiency/economy, stealth) that needed to be examined in animals for inspiration and the development of potential new designs that would be advantageous for marine propulsive systems.

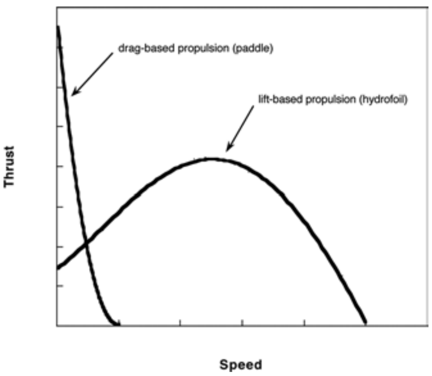
Speed

The most dominant attribute of performance is speed for both animals and engineered vehicles. Maximum speed and acceleration are often considered the most important factors of speed as they reduce the time to a target or destination and can quickly remove one from danger. For animals, these factors are subject to strong evolutionary selection pressures. However, lower routine speeds and long-term endurance can be equally important.

The performance of the drag-based and lift-based propulsive

FIGURE 1

Comparison of lift-based and drag-based thrust production in relation to swimming speed. Drag-based paddling can result in substantially greater thrust production than lift-based swimming when a body is stationary. As speed increases, drag-based paddling becomes less effective compared to lift-based thrust production. Redrawn from Vogel (1994).



systems is limited by swimming speed (Figure 1). Drag-based paddling operates most effectively at low speeds, whereas lift-based hydrofoils perform best at higher speeds. As a flow field needs to be established for a lifting surface to work, hydrofoils are limited in use to conditions where the body of an animal is already in motion. Paddles can be used when the body is stationary. A paddle of large area can impart sufficient momentum to a mass of water to induce recoil in a stationary body. The reaction force can be used to accelerate the body and produce a maneuver. Because the thrust production by the paddle is dependent on its movement in the direction opposite the body movement, thrust decreases as the velocity of the body increases. At a speed where the body and paddle speeds are equivalent, thrust can no longer be produced (Vogel, 1994).

The highest swimming speeds in animal systems are found for the oscillatory lift-based propulsors. Swordfish (*Xiphias gladius*) and marlin (*Makaira indica*) have the highest maximum speeds of 70 kts (Aleyev, 1977), which may only be for brief periods of time. This speed is faster than for fully submerged vessels, except when supercavitation is employed. Whales and dolphins can travel at speeds up to 22–34 kts (Fish & Rohr, 1999). Routine speeds for cetaceans, which are used for sustained cruising and long migrations, are 2.5–7.0 kts (Fish & Rohr, 1999).

Maneuverability

Standard engineered propulsive systems work in concert with control surfaces (e.g., rudders, fins, dive planes) to maneuver. In addition, lateral thrusters and vectored thrust mechanisms (e.g., water jet, outboard motor) can produce turns. While various marine organisms use similar mechanisms through combinations of fins (e.g., boxfish, cetaceans) and vectored thrust (e.g., squid), there are animals in which the propulsor can provide maneuvering control and thrust simultaneously.

The bluegill sunfish (*Lepomis macrochirus*) uses its pectoral fins to hold station, maneuver, and provide thrust. The control of the fin occurs through complex manipulation of the individual fin rays. Robotic fins have been developed to mimic the motions, forces, and flow control of the natural fins (Figure 2; Tangorra et al., 2011).

The manta ray (*Manta birostris*) and other batoid fishes have enlarged pectoral fins that act as propulsors, stabilizers, and control surfaces (Moored et al., 2011). The action of the manta's fins provides efficient thrust production for migration in the open ocean and enhanced maneuvering control around environmentally complex coral reef communities. The development of a robotic ray, based on the manta (Mantabot), has shown promise in its ability to maneuver (Figure 3). The flexible fins are actuated by an internal tensegrity skeleton (Fish et al., 2011). The Mantabot can execute

FIGURE 2

Biomimetic fish with fins controlled by mobile fin rays. Courtesy of J. Tangorra.

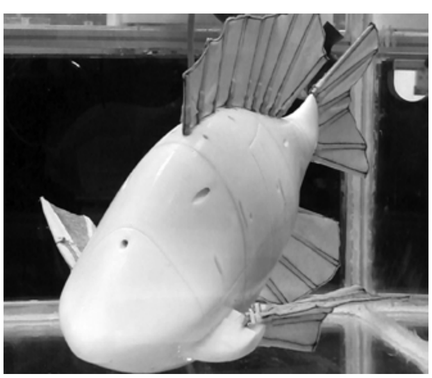


FIGURE 3

Sequential images of a swimming robot based on the morphology and kinematics of the manta ray (Mantabot). The pectoral fin is oscillated in the vertical plane by actuation of an internal tensegrity skeleton. The pathway of the oscillating fin tip is indicated by the sinusoidal trace. Courtesy of H. Bart-Smith.

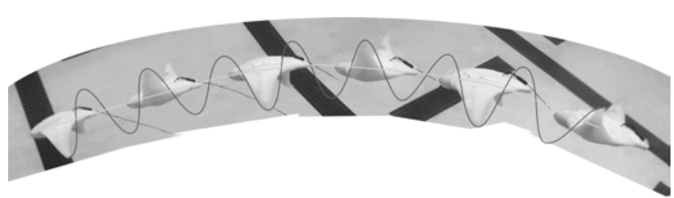
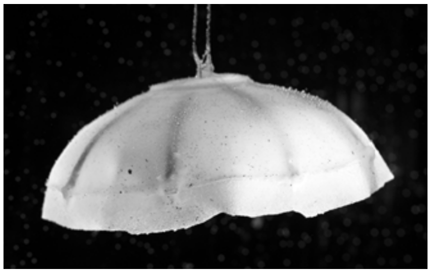


FIGURE 4

The Robojelly is an artificial jellyfish, which swims by pulsations of its bell-like body. Courtesy of S. Priya.



turns with a radius of 0.72 body lengths at over 59 deg/s; whereas, the AUV Remus turns with a radius of 2.9 body lengths at a rate of 9.9 deg/s (Stanway, 2008).

The ability to maneuver also involves swimming motion to maintain position and station hold, particularly when subjected to external perturbations. Animal propulsive systems can be used to generate thrust or increase drag to orient forces in opposition to currents, wave action, buoyancy changes, and collisions with other bodies. An artificial jellyfish (Figure 4) could hold position and operate in the open ocean over an extended deployment like the real jellyfish, whose swimming motions use minimal energy (Joshi et al., 2011).

Efficiency/Economy

Standard marine propellers are limited with regard to hydrodynamic efficiency. The efficiency of a typical marine propeller is less than 70% (Breslin & Andersen, 1994; Carlton, 2012; Larrabee, 1980). The efficiency of a propeller is dependent on the kinetic energy losses due to the rotation rate and swirl induced to the fluid. The energy losses of the propeller are largely due to friction drag on the blades, tip leakage, rotational flow, and propeller-induced axial/swirl flow (Larrabee, 1980; Olsen, 2004; von Backström et al., 1996). Axial losses account for the majority of kinetic energy losses under high thrust production (Breslin & Andersen, 1994). Many propellers have a fixed pitch of the blades, which limits the maximum efficiency to a narrow operational speed and load range (Fish & Lauder, 2006).

The thrust performance of animal propulsive systems has been considered superior to screw propellers (Peterson, 1925; Pettigrew, 1893; Triantafyllou & Triantafyllou, 1995). Although the efficiencies of paddle propulsion are less than 0.33 (Fish, 1996), body and caudal fin propulsion for fish and marine mammals efficiencies typically range from 0.7 to over 0.9 (Fish & Rohr, 1999; Webb, 1975). These high efficiencies are associated with lift-based thrust production from oscillation of a caudal hydrofoil. The oscillatory motions of flexible-bodied fish and dolphin tails were considered to be able to adjust to velocity changes and maintain effective thrust production over a large speed range (Fish et al., 2006; Peterson, 1925; Pettigrew, 1893; Saunders, 1951, 1957).

There are advantages to the application of the concept of an oscillating propulsor (Carlton, 2012; Vermeiden et al., 2012). There is the possibility of larger propulsive areas to accelerate a large mass of water and increase thrust production compared to the typical propeller. This action would reduce axial kinetic energy losses and would reduce the thrust loading of the blades to increase efficiency and reduce the likelihood of cavitation. When the area of the oscillating propulsor is distributed in a high aspect ratio configuration as displayed by a number of animals, there is reduced induced drag (Vermeiden et al., 2012). Furthermore, the flow regime over the blades would be almost two dimensional (chordwise). Such a flow enhances efficiency by reducing spanwise flow, which is associated with energy losses from the spin of a screw propeller.

The caudal fin of fish and flukes of cetaceans can be self-adjusting hydrofoils in which the highly flexible structure automatically alters its camber (Fish et al., 2006; McCutcheon, 1970). Thus, the caudal fin and flukes regulate the hydrodynamic load and distribute the load over the propulsor in the same way at all speeds. Vermeiden et al. (2012) found that the chord of a flexible oscillating fin had reverse camber at midstroke that produced a small gain in efficiency as the fin reversed direction at the end of the stroke. The flexibility of the fin associated with direction reversal suggested energy storage and recovery at the start of each stroke. This effect would be particularly prevalent with a highly flexible trailing edge as found in fish and marine mammals (Fish & Rohr, 1999).

Flexibility across the chord can increase propulsive efficiency (Bose, 1995; Katz & Weihs, 1978; Prempraneerach et al., 2003; Vermeiden et al., 2012). The efficiency of an oscillating, flexible hydrofoil is increased by 20–36% with a small decrease in thrust, compared to a rigid propulsor executing similar movements (Katz & Weihs, 1978; Prempraneerach et al., 2003). Cambering would change the flow over the propulsive surface to increase the lift generated. Cambering would be beneficial to maintain lift production at the end of each oscillatory stroke as the propulsor changes direction, when there is a period of feathering (i.e., parallel to the incident flow, producing no thrust and reducing efficiency).

Camber is provided in fish by the bony fin rays, which act like flexible girders when subjected to hydrodynamic forces (Flammang et al., 2013; McCutcheon, 1970). Movement of the half rays by muscle activation can also produce bending. The flukes of cetaceans can be bent along the axes of chord and span. Structurally, the flukes are lateral extensions from the tail, and there are no bony supports in the fluke blades. A model two-blade propeller with electroactive polymeric artificial muscles to induce cambering produced a 15% enhancement of thrust (Bandyopadhyay, 2002).

The efficiency of jet propulsion is lower than for swimming by undulation. Squids have a propulsive efficiency that is only one third of a similarly sized fish (O'Dor & Webber, 1986). The squid loses substantial kinetic energy as it must accelerate a smaller mass of water to a higher speed than a fish to obtain the same thrust. Although squid can accelerate as rapidly as fish (39 m/s^2), the squid uses more than twice the energy to travel half the speed of a fish.

FIGURE 5

Biomimetic glider that has a mobile caudal fin for low energy movement. Courtesy of X. Tan.

A substantial increase in efficiency in animals can be realized by using passive gliding. Negatively buoyant fish conserve energy by gliding downward with no propulsive motions and then regaining altitude by actively swimming. This strategy is used by AUV gliders (Figure 5; Tan, 2011).

Stealth

Submarines are almost, by definition, a form of stealth technology. The first submarine design to incorporate biomimetic propulsion was proposed by Borelli (1680). Propulsion would be accomplished by oars projecting through the hull and fitted with watertight seals. The oars would paddle like the feet of frogs or geese. During the power stroke, a flexible paddle at the end of the oar would expand to push on the water, whereas during the recovery stroke, the paddle would fold passively to reduce the drag on the oar. Borelli considered, however, that propulsion of the boat would be easier if a flexible oar were positioned at the stern emulating the motion of a fish tail. The development of such stealth technology would take centuries before becoming fully operational and then without biomimetic propulsion.

Propulsive systems move objects so that compression waves are propagated through the water to create hydrodynamic sounds. Much of the anthropogenic noise in the marine environment is the result of ship traffic. Propeller noise is the dominant factor with respect to the radiated noise signature of marine vessels (Carlton, 2012). Propeller noise is generated by displacement of the water, pressure differences between blade surfaces, flow over the blades, periodic fluctuations, and cavitation. Cavitation is due to the production of shock waves as bubbles formed from rapid pressure changes around the propeller blades collapse. Fully developed cavitation can emit a noise between 170 and 185 dB over a frequency range of 32 Hz–18 kHz (Carlton, 2012).

Large swimmers, such as dolphins and tunas, could experience cavitation at shallow depth at speeds of 5.1–7.7 kts, but this performance may be rare as cavitation would limit swimming speed (Iosilevskii & Weihs, 2008). The hydrodynamic sounds of swimming fish are generally low in frequency, which ranges down to subsonic (Tavolga, 1964a). The hydrodynamic sounds are nonharmonic with frequencies ranging from 100 Hz to below 10 Hz (Kasumyan, 2008; Moulton, 1960). These sounds are characterized as primarily near-field displacements and can only be detected over a short range when produced at a high intensity (Tavolga, 1964b). Body shape, speed, and trajectory of a swimming fish, and schooling affect the amplitude and frequency of the hydrodynamic sound produced (Kasumyan, 2008; Moulton, 1960).

Emulation is also a form of stealth. Biorobots that look identical with respect to the body form and swimming actions of an organism will blend into the natural environment. The problem with such mimicry is that other biological organisms may prey or parasitize the biorobot and thus degrade its performance or immobilize it. Sharks are known to bite oceanographic equipment, submarine cables, surfboards, and even submarines (Lowry et al., 2009; Papastamatiou et al., 2010). Sea turtles ingest plastic bags that have been misidentified as jellyfish, which are their natural prey (Carr, 1987). Future developments in aquatic biomimetic propulsion and biorobots will therefore have to consider rapid acceleration for escape or antibiofouling mechanisms for long deployments at sea.

Mission

The use of bioinspired propulsive system will probably never replace the general use of the screw propeller. The ubiquity of the screw propeller for marine applications is well established. It has only been in more specialized applications that novel modifications have been made to propeller designs. For example, water jet propulsion can be used in conditions requiring high efficiency, cavitation reduction, and low draught (Carlton, 2012); a pump-jet is quieter and more efficient than an open propeller (Zimmerman, 2000); and a ring thruster produces more thrust for a given power input than conventional thrusters (Holt & White, 1994). Cycloidal, vertical shaft propellers, such as the Kirsten-Boeing propeller and the Voith-Schneider propeller, are capable of high-efficiency propulsion or enhanced maneuverability and station-holding, respectively (Breslin & Andersen, 1994; Carlton, 2012; Jürgens & Fork, 2002). Contra-rotating propellers balance torques and provide directional stability in torpedoes.

Compared to an engineered propeller system, including the standard marine propeller, biomimetic propulsion can have enhanced performance with respect to speed, maneuverability, efficiency, and stealth. However, the use of biomimetic propulsive systems will be dependent on the specifications of a defined application or mission. Defining the mission requirements and matching them to the performance envelope of a biomimetic propulsor becomes crucial. Although biomimetic propulsion may have some utility or serve for inspiration to modify existing propulsion systems for large marine vessels, the benefits and applications in the near term will be confined to small robotic systems. Autonomous underwater vehicles can serve as test beds for developing biomimetic propulsion and find utility in performing missions that are outside the scope or performance levels of existing propeller technologies.

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