Unified Study for Various Types of Fish-Like Locomotion: Hydrodynamic Characteristics and Propulsive Performance under the Effect of Muscles and Flow-Induced Flexibility

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Extremely efficient performance of natural systems inspired scientists and engineers to imitate the natural phenomenon for engineering applications, leading to the evolution of a subject called "biomimetic". One of them is mimicking the motion of fish which move smoothly in water without spending a lot of energy. The extraordinary propulsive performance of fish as compared to conventional aquatic propulsion systems (such as marine propellers) is an upcoming topic of research for the efficient design of underwater drones or vehicles.

Majority of the fish comes under a category of Body-Caudal-Fin (BCF), which is further classified as anguilliform, sub-carangiform, carangiform, and thunniform types as shown in the figure. The classification is based on the type of movement adapted by the body and tail of fish. Note from the figure that all the types of fish have a tail (called as caudal fin) except the anguilliform fish. *Anguilliform fish* (such as eel) are thin, long, and use a *wavy undulation* over the whole body which pushes the fluid backwards and generates thrust force to move forward. *Thunniformfish* (such as shark and whale) have an almost stationary front part of the body and a crescent-shaped tail of hydrofoil cross section as seen in the figure, which undergoes a *pendulum-like oscillation* for thrust generation. With a change in the order from anguilliform to thunniform fish (as seen in the figure), the wavy undulation of the body decreases and the oscillation of the tail increases.

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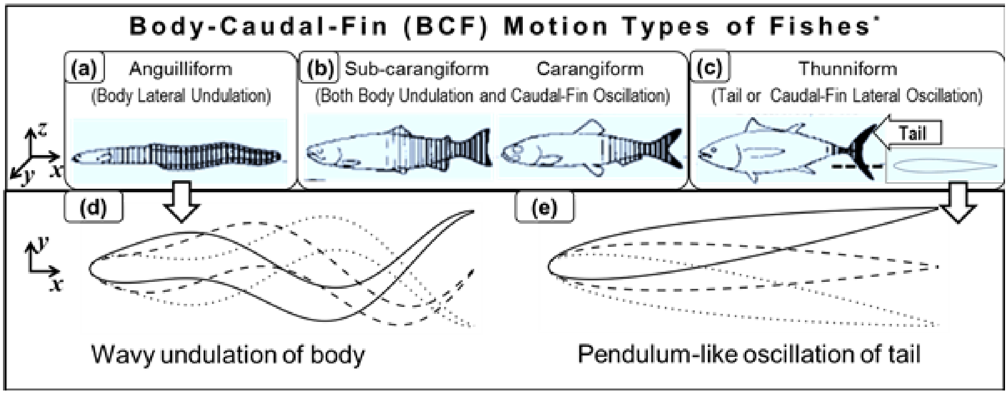

Figure 1: Change Fishes to Fish

Most of the fish use some kind of flexible motion for their movement in the water. Some fish generate a flexible wavy motion of their body and/or tail using the coordinated muscles movement, called as *muscles-induced flexibility*. When fish move, the surrounding unsteady and non-uniform water flow-based hydrodynamic forces may lead to deformation of certain parts of the body and/or tail of the fish, called *flow-induced flexibility*. Both the muscles and flow-induced flexibilities result in the efficient aquatic propulsion of fish, under various swimming conditions. The effect of both the types of flexibility on various types of fish-like locomotion is studied numerically by solving governing equations for motion as well as deformation of the body or tail of fish and motion of the fluid flow. The resulting coupled structural-dynamic and fluid-dynamic equations are solved using a computational method, called as *Computational Fluid-Structure Interaction (CFSI)*.

Recent researchers in this field focused mostly on the separate study of each of the various types of fish-like locomotion. A new two-dimensional computational study, published in journals Physics of Fluids (https://doi.org/10.1063/1.5041358) and Sādhanā (https://link.springer.com/article/10.1007/s12046-017-0619-7), by the author (under the guidance of Prof. Atul Sharma and Prof. Amit Agrawal at Indian Institute of Technology Bombay) proposed a unified kinematic model considering a hydrofoil for all the types of fish-like locomotion. This unified study will help to design efficient aquatic propulsion systems which take the advantages of all the types of fish-like locomotion.

Our unified kinematic equation is modelled in such a way that one extreme case represents the wavy undulation corresponding to the body of anguilliform fishes and the other extreme case represents the oscillation of the tail of the thunni form fishes. A parameter called as *wave-number* (number of waves present at an instant) controls the type of motion where a larger wave-number leads to the wavy undulation while a smaller wave-number leads to oscillation of the hydrofoil. We can also say that the wavy undulation represents a more flexible (muscles-induced) motion whereas the oscillation represents almost rigid motion. The intermediate wave-number based flexibility results in a hypothetical fish-like locomotion which corresponds to a combination of the wavy undulation and oscillation.

Our unified hydrodynamics study considered hydrodynamic characteristics and propulsive performance of the different types of fish-like locomotion. The term hydrodynamic characteristics corresponds to the characterisation of *flow patterns* of water around the fish body/tail – represented graphically by colour-contours of velocity, pressure, and vorticity (represents the rotation of the fluid) in the nearby flow region. Propulsive performance includes the propulsive thrust force (acting on the body) and efficiency. The undulation or oscillation in the *x-y* plane (as shown in the figure) results in the surrounding flow based hydrodynamic forces in both swimming (*x*) and lateral (*y*) directions. The force in the swimming direction – called *thrust force* – together with the swimming velocity results in the output power. Input power is required for the movement of muscles which generate the undulation and oscillation. The ratio of the output power to the input power is defined as the *propulsive efficiency*.

We found that oscillation of the tail generates larger thrust force as compared to the wavy undulation of the body of fishes. Our results are in agreement with that reported for real fish – the larger thrust force by the tail is needed for the movement of the heavy anterior part (with little lateral movement) of the thunniform fish (such as whale). Whereas, for less bulky and much thinner anguilliform fish (such as eels), the thrust force required is comparatively less. The oscillation of the tail needs a larger power input as compared to the wavy undulation of the body. To provide the larger power, thunniform fishes are heavier and stronger as compared with anguilliform fish. Furthermore, similar to the results for real fish, we found smaller efficiency for the oscillating tail as compared with the undulating body. Thus, oscillation can be recommended for an aquatic propulsion system with heavy load requirement at the expense of efficiency whereas a proper combination of oscillation and undulation can be used for light and intermediate loads to get the optimum thrust force and efficiency. Further, the wavy undulation is more efficient in the smaller velocity range; vice-versa for the oscillation-based swimming. This can be the reason why anguilliform fish swim at smaller velocity range as compared to thunniform fish.

Our results are correlated with the *stabilizing mechanism*which is used by the thunniform but not by the anguilliform fish. We reported that the wavy undulation of the hydrofoil pushes the fluid continuously throughout the entire body resulting in an almost constant thrust force, and hence an almost constant swimming velocity at all the time. The oscillation of the hydrofoil results in a reasonable time-wise varying thrust force and swimming velocity.These variations can be tolerated by thunniform fish since they have a bulky anterior body along with different types of fins to stabilise the body. Whereas, since anguilliform fish do not have such fins and the resulting stabilising mechanism, it is understandable that they experience time-wise invariant forces and velocity which does not have much effect on the stability of the body. Thus, for an almost constant swimming velocity, anguilliform type of motion is prescribed over the thunniform motion.

Our results are also correlated with the *sensing mechanism* of the real fish by the disturbance in the flow behind the foil. The disturbance generated by the wavy undulation of anguilliform fish is used by predator fish – mostly big fish coming under the category of thunniform fish. Theysense the disturbance in the flow generated by the prey fish (mostly small anguilliform fish) using their sensitive organs. Since the evolution is an arms race between predator and prey, the prey fish try to win over the predators by making the signals as weak as possible. Our results reported a weak disturbance produced by undulating hydrofoil which reduces the chance of detection of anguilliform fish by the predators.

Majority of the studies on fish-like locomotion including our work discussed above did not consider the flow-induced flexibility of the tail fin of thunniform fishes which helps to improve the propulsive thrust force and efficiency. We proposed a new study at the 71st Annual Meeting of American Physical Society, Division of Fluid Dynamics (http://meetings.aps.org/Meeting/DFD18/Session/F23.7), considering the effect of flow-induced flexibility on the oscillation of the tail for a wide range of structural flexibility. We found that the deformation (in addition to oscillation) results in the enhancement of thrust force and efficiency. The intermediate value of structural flexibility results in maximum bending of the hydrofoil (force induced deformation) which leads to the maximum thrust force and efficiency as observed in real fish.

Finally, the above muscle-induced flexibility study concluded that a proper combination of wavy undulation corresponding to anguilliform fish and oscillation corresponding thunniform fish can be chosen (by our generic parameter wave-number) to achieve a desired thrust force, propulsive efficiency, and swimming velocity. Furthermore, the above muscles as well as flow-induced flexibility study concluded that moderate flexible materials can be used for an enhancement of the thrust force and propulsive efficiency. From our research group at Computational Fluid Dynamics Lab IIT Bombay, similar unified studies will be presented for various energy efficient swimming modes and optimum shapes of the hydrofoil in future. The present study can be used for the design of fish-like *biomimetic underwater drones or vehicles*.