Biomimetic Undulating Fin Propulsion for Maneuvering Underwater Vehicles

K. M. Kalumuck*, A. Brandt*, M. Armand*, M. D. Kutzer*, C. Y. Brown*, N. J. Cowan[†], A. Prosperetti[†], C. Blizzard[†], R. Burns[†], M. Takagi[†], and E. S. Fortune[‡]

*JHU Applied Physics Laboratory, Laurel, MD; and JHU Departments of [†]Mechanical Engineering and [‡]Psychological and Brain Sciences, Baltimore, MD

The understanding gained from recent work on force production mechanisms of aquatic organisms holds great promise for improved undersea vehicle propulsion and maneuvering. One class of fish locomotion is that of the median fin used by animals such as squid, cuttlefish, knifefish, and seahorses. It is characterized by undulatory motion that creates traveling waves along the fin (Fig. 1).

Researchers at the JHU Whiting School of Engineering and the Zanvyl Krieger School of Arts and Sciences conducted observational experiments, obtained maneuvering/propulsion characteristics of different knifefish species, and developed a simplified analytical hydrodynamic theory.

Researchers at APL designed and built a submerged mechanical underwater undulating fin testbed that was used in experiments conducted in the APL Hydrodynamics Research Laboratory flow channel.

The model incorporates a 0.5-m-long fin mounted to a cylindrical body (Fig. 2). The fin consists of a flexible skin attached to ribs driven by an adjustable cam mechanism that is driven by a variable-speed motor. This configuration enables the characteristics of the undulating wave(s) to be changed. Forces produced by the fin were measured both in a captive mode under quiescent conditions and in the presence of an ambient current. Propulsive forces were characterized as a function of the fin width, oscillation frequency, amplitude, and wavelength. Free-swimming experiments were also conducted to determine the point of self-propulsion.

A key element of the success of any practical implementation of this form of propulsion and maneuvering is the ability to adjust the characteristics of the undulating fin, including its amplitude, frequency, and wavelength, while maintaining a compact and efficient drive mechanism. From an experimental testbed perspective, it is even more important to be able to easily adjust these characteristics. In operational conditions, changes in fin characteristics would be needed for vehicle maneuverability and would also improve efficiency. In any practical system, changes in fin operating characteristics would be directed by an onboard microprocessor feedback control system.

Toward this end, APL staff mentored a team of JHU Senior Design Project mechanical engineering students who successfully designed and fabricated a novel drive mechanism for continuously modulating the wavelength and amplitude of the undulating fins using a combination of only four drive motors. This novel, automatically adjustable cam-follower mechanism design enables an indefinite number of wavelengths within a given range, variable frequency, and a factor 3 range in fin undulation amplitude. The modular cassette design of the system enables quick changes (for testing) to the fin length, width, and number of undulating fin ribs (Fig. 3).

The results of the force measurements are consistent with simple theory and published data.[1–3] Specifically, the measured thrust was found to vary linearly with both the undulation frequency and the cube of the width of the fin. The net thrust is reduced when operating against a current with the reduction varying approximately lin-

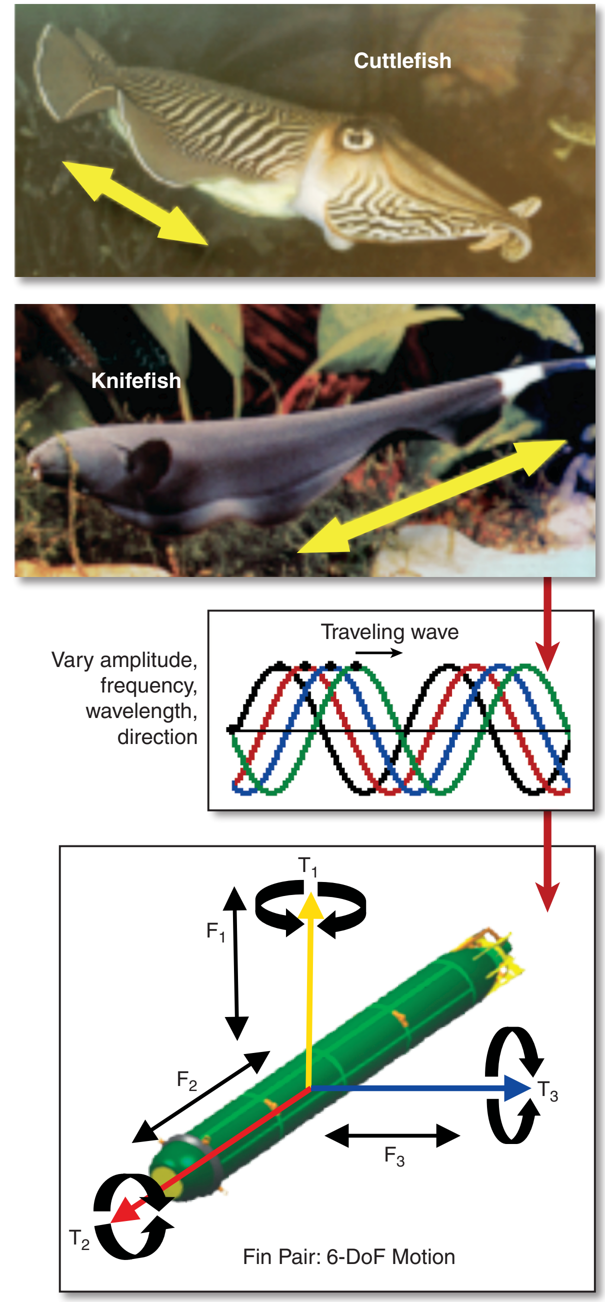

Figure 1. Cuttlefish and the black ghost knifefish maneuver by using an undulating fin and a mostly rigid body, allowing for rapid, agile movement, as well as hovering and a variety of other complex maneuvers. Using the knifefish as inspiration, APL created and tested the submersible model undulating fin shown in Fig 2.

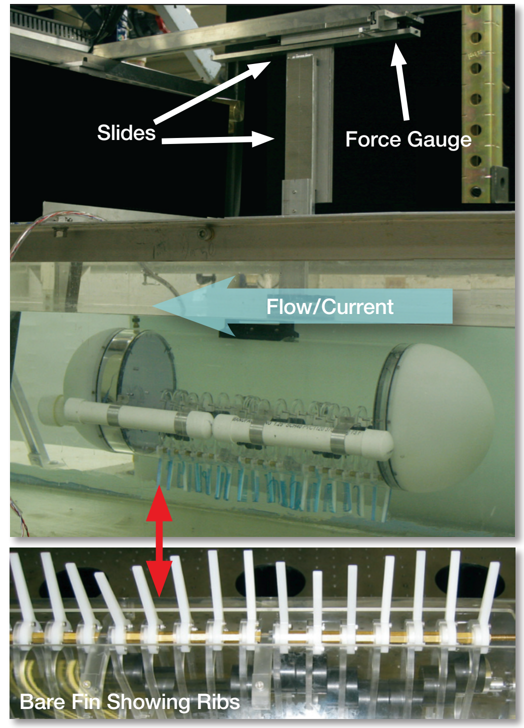

Figure 2. Undulating fin model tested in flow channel.

early with increasing current. The thrust per unit fin area was found to be consistent with the values found by others.[2,3] Comparisons with values for actual fish could not be made because thrust values for fish have not been measured. Scaling of the results indicate that model is a promising means for low-speed unmanned underwater vehicle propulsion and maneuvering.

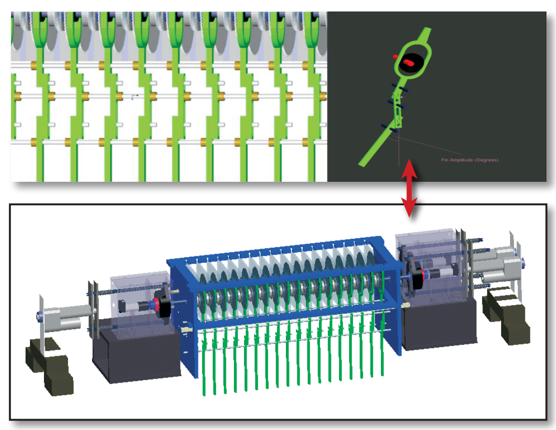

Figure 3. Novel adjustable fin mechanism.

For further information on the work reported here, see the references below or contact kenneth.kalumuck@jhuapl.edu.

[1]Lighthill, J., and Blake, R., "Biofluiddynamics of Balistiform and Gymnotiform Locomotion," *J. Fluid Mech.* 212, 183–207 (1990).

[2]Epstein, M., Colgate, J. E., and MacIver, M. A., "Generating Thrust with a Biologically Inspired Robotic Ribbon Fin," in *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Edmonton, Alberta, Canada, pp. 2412–2417 (2005).

[3]Sfakiotakis, M., Lane, D. M., and Davies, B. C., "An Experimental Undulating-Fin Device Using the Parallel Bellows Actuator," in *Proc. of IEEE Int. Conf. on Robotics and Automation*, Seoul, Korea, Vol. 3, pp. 2356–2362 (2001).