The Pneufish: A soft-robotic, pneumatic model for studying fish locomotion

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1 Introduction

Fish swim using a combination of active and passive movement [1, 2]. The most common type of active swimming is characterized by muscles producing an undulatory wave down the body of the fish. The undulating body imparts momentum to the water and the fish moves forward. Passive movement, in contrast, is when fluid pushes on the body, resulting in undulatory motion despite the lack of muscular involvement [1]. Animals may simultaneously generate active movement while experiencing the consequences of morphological characteristics that generate passive movement [1]. An established, simple model for researching fish locomotion uses a plastic foil (driven at the leading edge by a motor) to mimic undulatory motion (the “Flapper”). The Flapper model has led to tremendous insights into the effects of key variables on swimming performance [3–5]. However, the results apply solely to passive motion, as the Flapper is not active (self-actuating). The passive foil is sometimes too simple and the results do not always agree with live fish swimming data [5]. More complex, fish-like ‘hard’ robotic systems with gears, joints, and motors are active but complicated, and can be difficult to create, maintain, or alter [6]. This complexity hinders exploring fundamental questions and broad parameter spaces.

To satisfy the need for an easily-manufactured, easily-modifiable, self-actuating model, we have designed a soft-robotic fish model using pneumatic actuators, or pneunets. This apparatus is capable of producing positive thrust, and is an actively swimming model [7].

I have termed the apparatus the ‘pneufish’, and have constructed two versions: the duo-pneufish, made of one pair of activating pneunets, and the quad-pneufish, made of two pairs (Fig. 1C). In this paper, I explore the parameter space of both the duo- and quad-pneufishes to determine which parameters are most effective at improving swimming performance and producing realistic undulatory motion.

2 Experimental Design

Pneunets are molded using silicone rubber (Dragon skin 20, Smooth-On Inc., Easton, PA 18042, USA), and are inflated with air to produce motion [8]. Pneufishes are constructed by sandwiching a thin sheet of plastic, called the ‘backbone foil’ (flexural stiffness ranges between 8.1e-4 Nm² and 1.1e-2 Nm²), between either two or four pneunets.

3 Performance

The duo-pneufish and quad-pneufish were activated across a large parameter space, including backbone foil flexural stiffness (EI), frequency, air pressure, phasing, and flow speed in the flow tank. The digital pressure regulators can vary the maximum and minimum air pressure during activation, thus allowing for variable control of body stiffness post-manufacture, a novelty in swimming robotic systems.

An example of the duo-pneufish ‘s swimming performance is shown in Figure 2. The top graph shows the thrust, with the average thrust shown in blue. The positive mean indicates that the duo-pneufish would be accelerating in the water column, if it were untethered.

In Figure 3, we compare the midlines of a mackerel (A),
the duo-pneufish (B), and the quad-pneufish (C) at selected parameter combinations. The quad-pneufish is producing undulatory motion, unlike the duo-pneufish, and is therefore a more realistic for simulating and investigating undulatory motion going forward.

4 Discussion

In this study, we developed and compared two models, the duo-pneufish and the quad-pneufish, for simulating and investigating undulatory swimming locomotion. As the pneufish models are easily manufactured and modified, we believe this will be an ideal system to begin studying the effects of active swimming, in comparison to the results from the passive Flapper platform. Both the duo- and the quad-pneufish have allowed us to look at key parameter interactions, as well as begin integrating more complexity (such as muscle activation phasing) into our investigations of undulatory swimming.

References
