Available online at www.sciencedirect.com
ScienceDirect
Journal of Bionic Engineering 8 (2011) 418–428

A Flexible Fin with Bio-Inspired Stiffness Profile and Geometry

T. Salumäe, M. Kruusmaa

Centre for Biorobotics, *Tallinn University of Technology*, *Akadeemia tee* 15A-111, 12618, *Tallinn*, *Estonia*

Abstract

Biological evidence suggests that fish use mostly anterior muscles for steady swimming while the caudal part of the body is passive and, acting as a carrier of energy, transfers the momentum to the surrounding water. Inspired by those findings we hypothesize that certain swimming patterns can be achieved without copying the distributed actuation mechanism of fish but rather using a single actuator at the anterior part to create the travelling wave. To test the hypothesis a pitching flexible fin made of silicone rubber and silicone foam was designed by copying the stiffness distribution profile and geometry of a rainbow trout. The kinematics of the fin was compared to that of a steadily swimming trout. Fin's propulsive wave length and tail-beat amplitude were determined while it was actuated by a single servo motor. Results showed that the propulsive wave length and tail-beat amplitude of a steadily swimming 50 cm rainbow trout was achieved with our biomimetic fin while stimulated using certain actuation parameters (frequency 2.31 Hz and amplitude 6.6 degrees). The study concluded that fish-like swimming can be achieved by mimicking the stiffness and geometry of a rainbow trout and disregarding the details of the actuation mechanism.

Keywords: biomimetics, stiffness profile, fin, robotics, fish

doi: 10.1016/S1672-6529(11)60047-4

1 Introduction

Most of marine and underwater mechanisms, such as ships, submarines, or underwater robots use screw propellers for propulsion. Although these devices work sufficiently well for most purposes, the systems designed by nature still outperform them. Fish are able to swim with high velocities while maintaining superior agility and efficiency. Therefore they can be taken as inspiration when designing new kind of propulsion mechanisms.

Based on the theoretical knowledge of fish swimming[1,2], a variety of studies on devices mimicking fish to generate propulsion in liquid environments have been conducted. Most of these devices use rigid links and discrete mechanisms to achieve fish-like motion, dynamics and behaviour[3–7]. The complexity of these systems increases along with the increasing similarity with fish kinematics and therefore in turn decreases the swimming efficiency of the device.

Another alternative is to use compliant bodies which, when actuated from a single point, carry a travelling wave. This wave is similar to the propulsion wave in the body of fish, which instead of median or pectoral fins use their body and the caudal fin for generating propulsion. The oscillating wave travels through the body with a velocity higher than the swimming speed of the fish[1]. Compliant bodies carrying a similar travelling wave using single-point actuation can be modelled as dynamically bending beams[8], which have vibrational characteristics determined by the external and internal forces of the system. The vibrational characteristics in turn are related to geometry, material properties and actuation. The geometry and material properties together define the stiffness of the body which has a high impact on the swimming of both biological fishes[9–11] and compliant fish-like bodies[12,13]. Therefore the stiffness of compliant underwater fin propulsors has been studied thoroughly to increase the efficiency and control of fish-like devices and flapping foils.

McHenry *et al*. showed that body stiffness controls swimming kinematics and therefore the speed and performance of elastic models of pumpkinseed sunfish during steady, undulatory swimming[13] and Prempraneerach *et al*. proved the same for an oscillating NACA0014 foil by demonstrating that the efficiency of

Corresponding author: T. Salumäe
E-mail: taavi@biorobotics.ttu.ee

a pitching and heaving foil can be higher than that of a screw propeller[12]. Both studies investigated the influence of global stiffness on a compliant body. Riggs *et al*.[14] investigated the importance of stiffness profile along the elastic fin by taking experimental stiffness profile of a pumpkinseed sunfish from McHency *et al*.[13], casting flapping foils with the same profile but with a different absolute stiffness value, and comparing the preformance with NACA profiles. They showed that fish-like stiffness profile can increase the performance of flapping foils. However, they did not take into account the geometry of the fin and the exact stiffness values. Biomimetic stiffness variation along the body was also justified by Akanyeti *et al*.[15]. They showed that the increasing elasticity towards the tail will increase the performance of a foil.

As an alternative to an experimental approach, a theoretical analysis can be used to find properties of a compliant propulsor. Alvarado and Youcef-Toumi created a beam model of a compliant single-actuation mechanism and calculated the design parameters of a carangiform-swimming fish-robot[16–18]. The resulting mechanism's swimming performance attained one third of the real fish's performance and considerable errors in the targeted kinematics were reported. This may indicate that our current theoretical knowledge of nonlinear compliant vibrating systems with water interactions is not advanced enough to accurately describe the required kinematics and dynamics of the system.

Motivated by the above mentioned theoretical and empirical studies on fishlike motion of compliant flapping foil propulsion systems, this study presents a method for biomimetic design of these mechanisms. In Ref. [15] we argued that stiffness, stiffness profile and geometry are design parameters interrelated with each other in a complex manner and they all have impacts on the resultant kinematic characteristics of the propulsor. We therefore show a method of experimentally determining those characteristics from a rainbow trout and a method of building an artificial propulsor with the same parameters. The general methodology is as follows:

(1) Geometry and stiffness distribution along the body of a 50 cm long rainbow trout is characterized experimentally.

(2) An artificial fish tail (flapping foil) following the same geometry and stiffness profile is produced. A composite model made of two silicone materials with different properties is used to mimic both the desired geometry and stiffness profiles.

(3) Kinematics and swimming performance of artificial tail are determined and compared to those of a real steadily swimming rainbow trout.

The hypothesis of the study is that if the stiffness distribution and geometry of a flapping foil are the same as those of a real trout and the foil is actuated from a single point using sinusoidal angular motion, the foil will produce undulatory motion with kinematic parameters similar to those of a real swimming fish. The hypothesis is based on the fact that fish are able to swim at low cruising speeds with undulatory motions using only their anterior muscles[19,20]. Posterior body acts passively to carry a travelling wave and transmits locomotor power from the anterior muscle to the caudal fin[21]. In our mechanism, the rotational single-point actuation acts as an anterior muscle and the flapping foil should response to actuation similarly to the body of a living fish due to the same geometry and stiffness properties. If the similar kinematic behaviour of a steadily swimming rainbow trout is achieved with the single point actuator, it will show that for a biomimetic caudal fin propulsor the body stiffness and geometry play greater role than the actuation mechanism and a complicated undulatory motion can be achieved without copying the complex distributed actuation system of real fish. Those results can then be taken into account when designing biomimetic propulsors for low mechanical complexity.

2 Materials and methods

2.1 Test subject

To determine the stiffness and stiffness profile, the properties of a rainbow trout (*Oncorhynchus mykiss*) were measured. The specimen with the length of 0.5 m and the weight of 1.58 kg was caught from a fish farm. The experiments were conducted shortly after the death to prevent the change of body properties that might affect the characterisation results.

2.2 Bending stiffness experiment

The first experiment carried out on the test subject was the characterisation of the bending stiffness distribution along the body. The bending stiffness $\kappa(x)$ along the longitudinal axis x of the fish body can be evaluated as the ratio of moment $M(x)$ applied at single point to the