Fish swimming & maneuvering hydrodynamics

Brenden Epps
Thayer School of Engineering
May 10, 2013
questions?
How does a fish swim?

It flaps its tail!
What more is there?

- performance
- kinematics
- forces

robot fish: body and tail form, actuation, control, cost, manufacturability, service, battery life, etc.
Why is this difficult?

robot fish: body and tail form, actuation, control, cost, manufacturability, service, battery life, etc.
Outline

maneuvering

swimming

flapping foil propulsion
maneuvering
maneuvering (slow motion)
vortex rings
experiments

particle image velocimetry (PIV)

- typical maneuver lasts 0.25 seconds
- acquire images at 500 fps
- need camera, laser, software, and patience
Vector field and vorticity contours shown

Anticlockwise vorticity in red

Clockwise vorticity in blue

Static vorticity due to motion of ambient fluid

Ignore data in the fish shadow
kinematics

stage 1: preparatory stroke
stage 2: propulsive stroke

Monday, May 13, 13
maneuvering dynamics

- For a vortex ring:
  \[ I = \rho \Gamma \frac{\pi D^2}{4}, \quad \Gamma = VD \]

- By conservation of momentum:
  \[ \sum_{i=1}^{2} \vec{I}_{\text{fluid}} = \Delta \left( m \vec{V}_{\text{fish}} \right) \]

81 gcm/s  \hspace{2cm} 78 gcm/s

172°  \hspace{2cm} 133°

related research

- Gharib: “formation number” of piston-cylinder vortex rings

- Is there an “optimum” vortex ring for maneuvering?
- What is the best tail shape and flexibility, and best stroke kinematics to make an “optimum” vortex ring for maneuvering?
Taylor GI (1952) Formation of a vortex ring by giving an impulse to a circular disk and then dissolving it away. J. Applied Phys. v.24, no.1, pp.104-5

swimming
swimming (slow motion)
vortex chain

Nauen and Lauder, JEB 2002

laser plane

Nauen and Lauder, JEB 2002
kinematics
swimming speed \[ U = \ell \cdot f \]

phase speed \[ C = \lambda \cdot f \]

for thrust: \[ C > 1.2 \cdot U \]

therefore \[ \lambda > 1.2 \cdot \ell \]

5.1.1 Actuation Mechanism

The required actuation can be implemented using rotational or linear actuators. For the design examples presented in this chapter, RC (radio control) servo motors are used. Figures 5-2 and 5-3 display different views of two transmission designs used in the prototypes. A transmission consists of a servo, a servo support, a rigid plate, and mechanisms to transmit the servo forces to the rigid plate. A chosen transmission mechanism is then embedded inside the fish-like compliant body. During actuation, the transmission rigid plate applies the forces from the servo to the compliant body. Figure 5-2 shows a transmission mechanism that uses two cables attached to a servo motor to transmit torque to the rigid plate. Figure 5-3 shows an alternative mechanism that uses a flexure linkage connected to the rigid plate to transmit the required torque to a section inside the body. In this configuration, the servo arm acts as the coupler link and the rigid plate is the ground link. The cable mechanism is simpler and more easily scalable. However, during a cycle the cable mechanism only transmits

\[ \sigma = E \varepsilon + \mu \dot{\varepsilon} \]

Viscoelastic material: Silicone/polyurethane gel:

\[ E \sim 10^3-10^5 \text{ Pa}, \quad \mu \sim 1-100 \text{ Pa}\cdot\text{s} \]

Modified Bernoulli-Euler beam equation:

\[
\left( M - EI h'' - \mu I \dot{h}'' \right)'' = \left( \rho A + \rho_w \frac{\pi}{4} b^2 \right) \ddot{h}
\]

Desired tail kinematics:

\[
h(x = \ell, t) = H \sin(\omega t)
\]

5.1.1 Actuation Mechanism

The required actuation can be implemented using rotational or linear actuators. For the design examples presented in this chapter, RC (radio control) servo motors are used. Figures 5-2 and 5-3 display different views of two transmission designs used in the prototypes. A transmission consists of a servo, a servo support, a rigid plate, and mechanisms to transmit the servo forces to the rigid plate. A chosen transmission mechanism is then embedded inside the fish-like compliant body. During actuation, the transmission rigid plate applies the forces from the servo to the compliant body. Figure 5-2 shows a transmission mechanism that uses two cables attached to a servo motor to transmit torque to the rigid plate. Figure 5-3 shows an alternative mechanism that uses a flexure linkage connected to the rigid plate to transmit the required torque to a section inside the body. In this configuration the servo arm acts as the coupler link and the rigid plate is the ground link. The cable mechanism is simpler and more easily scalable. However, during a cycle the cable mechanism only transmits...
particle image velocimetry

- Vector field and vorticity contours shown
- **Anticlockwise** vorticity in red
- **Clockwise** vorticity in blue
- Static vorticity due to motion of ambient fluid
- Ignore data in the fish shadow
dye visualization
top view (1/3 speed)

side view (1/3-speed)

swimming speed

![Graph showing swimming speed vs flapping frequency]

- Live fish: 0.15 [L/s]/[Hz], 0.59 [L/s]/[Hz]
- RoboFish: 0.15 [L/s]/[Hz]

- Low freq.
- Nominal
- High freq.
wake geometry

\[ S_{tH} = \frac{fH}{U} \neq \text{constant} \]

\[ S_{tw} = \frac{f_w}{U} \approx \text{constant} \]

BP Epps, P Valdivia y Alvarado, K Youcef-Toumi, AH Techet,
Flow visualization studies of the swimming performance of biomimetic compliant fish-like robots. (in preparation.)
related research

optimal Strouhal number

\[ \text{Re} = 10^4 \cdot 10^6 \quad \text{St}_H = 0.3 \]
Fish Exploiting Vortices Decrease Muscle Activity
Science 302, 1566 (2003);
From: David Beal <dnbeal@alum.mit.edu>
Subject: Dead fish video
Date: April 28, 2009 3:35:18 PM EDT
To: Brenden Epps <bepps@mit.edu>

This video shows the dead fish in slow motion moving forwards. The blue line shows the length of the line it was attached to the cylinder with. The red line shows approximately the back of the suction region behind the cylinder. The fish's interaction with the cylinder's shed vorticity is what causes it to move forwards to that point. I also attached a real-time version.

Dave

Fish Exploiting Vortices Decrease Muscle Activity
Science 302, 1566 (2003);
oscillating foil propulsion

**Figure 3.** Visualization for flexible flapping foil at Strouhal number $St = 0.25$, maximum pitch angle $\alpha_0 = 15^\circ$, and phase offset $\phi = 90^\circ$. 

`MIT Center for Ocean Engineering, 2005`
oscillating foil propulsion

Isometric view of vortex shedding behind flapping foil at $St = 0.35$, $\alpha = 10^\circ$, and $\phi = 60^\circ$. Arrows indicate direction of vorticity vector.

MIT Center for Ocean Engineering, 2005