How to Tune a Tuna: Resonance of Locomotor Structure

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Final presentation slides:

Narration of final presentation:
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General Objective

- Further understand the mechanism of energy transfer between the tuna’s internal locomotor structure and the surrounding fluid medium.

Research Questions

- What is the “natural frequency” of the tuna locomotor system?
- Is this frequency comparable to the tailbeat frequencies and swimming speeds most commonly observed in wild and captive tuna?
- [future work] Is this frequency comparable to that of vortex shedding from a tuna’s body at different speeds and scales?

Model

I built the following simple model in OpenSim:

This represents the last set of musculotendon actuators in the tuna locomotor system (see Figure 5, later, for actual anatomy). I filled in the key parameters for this model (right) using information from literature and my own previous experience and measurements of dissecting tuna.

Some assumptions:

- keel (ellipse) is currently fixed to the ground - in reality it moves back and forth driven by the rest of the fish (Figure 3, later), but I am focusing on the tail flick
- tail is pin joint - in reality a set of several vertebrae with higher flexibility than the fairly rigid keel made up of several almost-fused vertebrae
- two linear musculotendon actuators inserting on either side of the tail, with single wrap point - in reality, some parts of the tendon also attach to the skin
- origin of actuators is fixed - in reality, the muscles anterior pull the others forward as they contract

Things to confirm that would improve the model:

- correct mass and inertial properties for tail
- maybe get a cool shape, just for 3D visualization purposes
- correct coordinate limits and coordinate limit force values incorporating vertebrae bending research
- correct muscle parameters to represent tuna
  - select values to feed into existing musculotendon model (some research indicates that shark red muscle operates similar to mammalian, and that tuna tendons are mammal-like)
  - do some geometry for initial muscle conditions so not pre-stretched (or are they pre-stretched in tuna? hm)

Approach 1 - Frequency Sweep

One experimental approach for determining natural frequency is by driving a system at a range of frequencies and measuring the resulting amplitude, which generates a plot something like this:

The highest amplitude responses occur when the driving frequency is near the natural frequency. I successfully drove my model in a forward simulation with muscle activations at 2.5 Hz. The next step would be to automate the workflow to make a plot like the one above.

Approach 2 - Impulse Response

Another way to experimentally measure natural frequency is to displace the system and observe the response upon release. When you plot the angle over time, you can measure the frequency, which ends up at around 10 Hz for no muscle activation and 26 Hz for complete
Approach 3 - Determine Stiffness

A final, somewhat more theoretical way to determine natural frequency is to fill out the below formulas for natural frequency and damped natural frequency.

\[ \omega_n = \sqrt{\frac{k_r}{I_y}}, \quad \omega_d = \omega_n \times \sqrt{1 - \zeta^2} \]

That requires finding rotational stiffness \( k_r \), rotational moment of inertia \( I_y \), and damping \( \zeta \). Rotational stiffness is the change in torque required to achieve a change in angle, which can be expressed as a differential quantity. The moment of inertia is fairly straightforward to find using the mass properties of the tail fin. Damping is more difficult to determine, from tissues and surrounding fluids, but in any case we know it will reduce the damped natural frequency.

Below is what a moment vs. angle plot for the tail joint in looks like from OpenSim. This one is for 0.5 muscle activation. I take the slope around the joint center position for my stiffness calculation. For full coactivation I get 21 Hz, half 18 Hz, and zero activation 10 Hz – which is fairly consistent with the results from my previous impulse response test.

Compare to Observed Behavior

Now I want to compare these various results for my tuna tail model's natural frequency to the speeds and tailbeat frequencies of live tuna. This depends on what the tuna is trying to do, like cruise efficiently or escape effectively. In a study of wild tuna filmed from a ship, we see tailbeat frequencies of around 2-14 Hz. We can zoom in on the more "relaxed" section of this graph with a more recent study using captive tuna in a water treadmill. They plot relationships between swim speed, tailbeat frequency, and cost of transport. Although cost if transport is fairly constant, we see the "most efficient" swimming seems to happen at around 2 Hz.

These values are in the range of my model results, which do not even include the damping effects of other tissues and the surrounding fluid, which would decrease my values for damped natural frequency.

Challenges and Future Work

As with any biomechanics modeling and simulation project, this came with many challenges and ideas for the future. My primary challenge was (and still is) making sure this model represents the actual biological system well enough to draw meaningful conclusions. One way to increase confidence in the results would be to run a sensitivity analysis of the model parameters, like the muscle and joint properties. It might also be informative to create a more complex model. For instance, former Delp lab members Melinda Cromie and Matt Millard have created a kinematic tuna model. Adding force properties could make it a useful tool to explore natural frequency. Finally, a key part of this research direction is to see how internal biomechanics and external fluid dynamics interact to power swimming. Comparing biomechanical natural frequencies to the frequencies that water vortices roll off the body shape at different speeds can help us understand how tuna tune their internal biomechanics to interact with their fluid environment.

Software

You can download the OpenSim model I created here: TunaTailModel.osim

2.5 Hz muscle-driven forward simulation

settings: 1 sec, equilibrium actuator states, force reporter
initial states: Tuna_initial_states.sto
controls: Tuna_controls_waggle.xml

Impulse response forward simulation

settings: 1 sec, equilibrium actuator states, force reporter
initial states: Tuna_initial_states_impulse.sto
To generate the plots I used to determine stiffness, I simply used the Plot tool and selected to plot moment of each muscle (and the sum) over the angle range of the tail.

Some of my research for filling in my model parameters: 485tuna-model-params.xlsx

A Mathematica notebook file (and PDF printout) for various calculations pertaining to the model and frequencies: 485tuna.nb, 485tunanb.pdf

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**Extra Background for Reference**

Tuna, one of the top predators in the ocean, swim with an incredible mix of power, speed, and efficiency. In this “thunniform” swimming, the front part of the body remains fairly straight. Bending the last part of the spine swings the stiff tail region right before the fin, called the peduncle, back and forth. The tail fin, in turn, bends relative to this peduncle, adding a characteristic flick to the tail strokes. Figure 1 shows this combined mode of oscillation.

**Figure 1** – Tail motion of a swimming tuna (Dimitrov et al. in preparation). Note the two primary motions of interest: that of the peduncle at the end of the spine, and that of the tail fin relative to the peduncle.

(sorry, not published yet, but here is a video where you can get the idea)

This gives the tuna fine control over the interaction between vortices coming off the body and those generated by the tail, as modeled with computational fluid dynamics (CFD). Vortices are rotational patterns of fluid motion that a fish creates while swimming, generating force and leaving the equivalent of footprints in the water (Fig. 2).

**Figure 2** – 3D fluid structure behind an oscillating tuna tail fin modeled using CFD (left), and a 2D slice of that (right), showing how the vortices form almost like “footprints.”

During cruising, tuna swim by almost exclusively using a system of red muscle myomeres, ribs, and posterior oblique tendons (POTs), shown in Figure 3, which transmit muscle forces to the spine. The horizontal ribs coming out of each vertebra act as struts, allowing the muscle attached to each tendon to pull on a vertebra farther down the spine. Figure 4 shows how these muscles contract along the body throughout the swimming “stride.”

**Figure 3** – A 2D engineering model (left) of the red muscle and posterior oblique tendon (POT) system in tuna (right), with the normally stacked muscles separated and folded out (Cromie et al. in preparation).

(sorry, not published yet, but here is a figure mashup from another paper that illustrates it)
Figure 4 – Muscle activation patterns of a swimming yellowfin tuna. From the head towards the tail, the muscles on one side start contracting, until they are all contracted. This then repeats on the other side of the body.²

Posterior to this POT system, a bony keel jutting out horizontally from the vertebrae acts to increase the moment arm of the great lateral tendon (GLT), which attaches to the tail fin (Fig. 5). Passing over the keel rather than lying close to the backbone provides the GLT and associated muscle myomeres with greater mechanical advantage as they pull on the tail. The GLT also attaches to the skin at various points on the way back to the tail.

Figure 5 – The great lateral tendon (GLT, blue) and associated muscle myomeres (red) of a yellowfin tuna (Dimitrov et al. in preparation).

(sorry, not published yet, but here is a photo from another paper illustrating the anatomy)³
References